KAHO'OLAWE WATER RESOURCES STUDY:

STRATEGIES FOR THE MANAGEMENT OF LAND & WATER RESOURCES

Kaho'olawe, Hawai'i

Report R - 82

State of Hawai'i
DEPARTMENT OF LAND AND NATURAL RESOURCES
Land Division
Honolulu, Hawai'i
Concluded in 1990
Final Submission in July 2001

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TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES

FOREWORD

This study of the water resources of Kaho'olawe was concluded and a pre-final report was submitted to the Department of Land and Natural Resources in October 1990. The final edited version was submitted in March 1998.

During the intervening period significant changes occurred in the status of the island which have profound implications for management and development of the island's natural resources, particularly water.

On October 22, 1990 President George Bush directed the Secretary of Defense to discontinue use of Kaho'olawe for bombing and target practice.

In November 1990 Congress established the Kaho'olawe Island Conveyance Commission (KICC) to recommend the terms and conditions for the return of the island to the State of Hawai'i. The Commission conducted 21 studies of the island's natural and cultural resources and ordnance hazards. These are listed at the end of the reference section for the reader's information and future reference.

Based upon the final recommendations of the KICC, Congress voted in November 1993 to permanently stop all military training and bombing of Kaho'olawe and return title of the island to the State of Hawai'i. Congress also authorized funding for the cleanup and restoration of the island's cultural and natural resources through the year 2003.

On May 7, 1994, Kaho'olawe was returned to the people of Hawai'i. Under state law, Chapter 6K, Hawai'i Revised Statutes, the island will serve as a cultural reserve and be held in trust for the sovereign Native Hawaiian entity when it is re-established and recognized by the state and federal governments. The state established the Kaho'olawe Island Reserve Commission (KIRC) to manage the island.

The Protect Kaho'olawe 'Ohana/Fund which conducted this water resources study interacted and participated in these developments. In part, this contributed to the delay in completing the final editing of the report. Another factor delaying completion, was the loss of the leading member of the team to cancer in January 1995.

The healing and restoration of the natural and cultural resources of Kaho'olawe is the primary goal of the KIRC, as reflected in the vision statement which they adopted in December 1995 to guide future use of the island:

The kino of Kanaloa is restored. Forests and shrublands of native plants and other biota clothe it slopes and valleys. Pristine ocean waters and healthy reef ecosystems are the foundation that supports and surrounds the island.

Na po'e Hawai'i care for the land in a manner which recognizes the island and ocean of Kanaloa as a living spiritual entity. Kanaloa is a pu'u honua and wahi pana where Native Hawaiian cultural practices flourish.

The piko of Kanaloa is the crossroads of past and future generations from which the Native Hawaiian lifestyle spreads throughout the islands.

In the conduct of this water resources study, the Protect Kaho'olawe 'Ohana/Fund acknowledges and is grateful for the leadership and inspiration of 'Ohana team member, the late Rendall Tong. His training and experience with the U.S. Geological Survey Water Resources Division was indispensable in the coordination of the study among the three major parties - The Department of Land and Natural Resources, the U.S. Geological Survey and the Protect Kaho'olawe 'Ohana/Fund.

The Protect Kaho'olawe 'Ohana/Fund also expresses aloha for the committed work of the team members - Ricky Apana, Tuti Baker, Keoni Fairbanks, Henry Hildebrand, Dan Holmes, Malia Huber, Annette Mente, Burt Sakata, Elaine Wender, and Greg West. Finally, mahalo for donated air transport time to Pacific Helicopters.

EXECUTIVE SUMMARY

This document reports the results of an eight-month investigation of the surface and ground water resources of Kaho'olawe, Hawai'i. The study was conducted by the Protect Kaho'olawe 'Ohana (herein referred to as "the 'Ohana") for the State of Hawai'i with a legislative appropriation of $75,000 from the State through its Department of Land and Natural Resources. The U.S. Geological Survey Water Resources Division also participated in the study through a matching fund agreement between the State and the U.S. Geological Survey. Significant findings are cited below.

Significant Findings

1. ***Land use practices on Kaho'olawe in the last century have altered the hydrologic cycle of the island,*** changing the balance between surface water runoff, ground water recharge, evaporation and effective precipitation. Over 70% of the water resource is lost as uncontrolled surface runoff on Kaho'olawe. Surface runoff velocities pose a severe erosion hazard to barren soils and watersheds of Kaho'olawe.

2. ***Water-induced soil erosion poses a serious threat to the stability of archaeological sites on Kaho'olawe.*** Many sites appear to have lost structural integrity since surveyed in 1976-1980, with site remnants scattered by infrequent but large and destructive runoff events.

3. ***Soil erosion rates from water alone range between 57-559 tons per acre on an annual basis.*** Individual rainfall and runoff events send thousands of pounds of sediment into surrounding coastal waters and are a significant source of non-point source pollution.

4. ***A ground water body on the northeastern part of Kaho'olawe was discovered by the U.S. Geological Survey using geophysical techniques.*** The feature covers an area of approximately 15,000 acres. The average thickness of the freshwater head is 300 feet, and its greatest thickness ranges from 600 to 700 feet. The feature appears to be dike-impounded water. A drilling program is the next step to evaluate the yield, quality, and most effective development plan. Some shallow perched ground water exists during the winter rainy period and after storms. A

thin basal lens of ground water exists at the mouths of the major gulches.

5. *The project successfully established one stream flow recording station, one rain gage, one ground water level recorder, eight soil and water conservation structures, three rainfall catchments and one runoff catchment in two watersheds covering an area of over 700 acres.* Data are already available from these instruments, enabling the development of water resource planning information. Another stream gage is scheduled for installation upon execution of a maintenance agreement between the resource management parties.

6. *Installation of project runoff and rainfall catchment devices demonstrate the potential to harvest sizable and usable quantities of water for revegetation and domestic needs.*

7. *Installation of project check dams demonstrate that water-induced soil erosion is a significant problem on Kaho'olawe and that properly constructed check dams using local materials are viable soil erosion control strategies.* Project check dams captured over 4,000 cubic feet of soil during the period October 1988-February, 1989.

8. *Water supply needs for Kaho'olawe* include approximately 96,500 gallons annually to support the Maui County Kaho'olawe Community Plan activities, over 350,000 gallons annually to support critically needed conservation efforts, and 170,000 gallons to support Navy use of Kaho'olawe as a bombing range and training facility for a total of 616,500 gallons annually.

9. *Investigation reveals that there are five primary sources of water on Kaho'olawe* to support a selected range of activities. The island's potential lies in rainfall harvesting, ground water development, and in the development of surface runoff catchment systems. Desalinization of brackish basal ground water and water importation offer additional sources.

Water supply studies indicate that a minimum of 129,000 gallons could be developed on an annual basis on Kaho'olawe from rainfall alone. If a program of catchment development was pursued over a five year period, this capacity could be expanded to harvest over 1,000,000 gallons of water per year. The potential for rainfall harvesting is limited only by the amount of rainfall and the availability of catchment surface.

The dike-impounded ground water resource offers a potential 150,000-350,000 gallons annually for revegetation purposes. Desalinization of brackish basal ground water could provide an additional 65,000 gallons of fresh water annually to Kaho'olawe base camps.

10. *Certain conservation programs and land use practices currently underway conflict with other conservation strategies for Kaho'olawe.* Conflicts involve the timing, methodology and placement of structures and the physical results of each strategy on water, soil and vegetation resources. The study concludes that conservation practices and programs for Kaho'olawe must achieve greater coordination if collective efforts are to be successful in arresting soil erosion, preserving archaeological features, reducing pollution of the marine environment and revegetating the island.

11. *A resource management and development plan for the land and water resources of Kaho'olawe is identified* which calls for a methodological, planned, and coordinated approach to restoration of Kaho'olawe's watersheds. A plan for the orderly development of surface and ground water resources on Kaho'olawe is proposed. Specific resource management strategies are proposed for a number of watersheds on Kaho'olawe.

12. *Six specific recommendations are identified* which address certain resource problem areas, immediately-needed conservation efforts, and the long-term organization and direction of resource management programs. These include:

> **Recommendation One.** A minimum of $2.5 million over the next two years should be committed immediately to support the critical revegetation and soil conservation work needed for Kaho'olawe. Specifically, an active water development program for the island should begin as soon as possible and should consist of: (a) the renovation of existing and development of new runoff catchment systems, (b) rainfall harvesting programs and (c) ground water development.

> **Recommendation Two.** Resource management activities on Kaho'olawe should continue with a program focused on the construction of effective check dams and headcut control structures in the tamarisk tree area, the development of water supplies, revegetation of selected areas and the development of specific erosion control projects for critically eroding regions of the hardpan area.

> **Recommendation Three.** A Kaho'olawe Watershed Restoration Task Force should be established to coordinate, oversee and implement the stabilization of approximately 15,000 acres of severely eroded land on Kaho'olawe over a 5-10 year period. The Task Force should be composed of all organizations and agencies actively pursuing resource management activities on the island including the Protect Kaho'olawe Fund, high-level

staff and directors of the State Department of Land and Natural Resouces, and the U.S. Navy as well as members of the State Legislature, appropriate technical personnel from the University of Hawai'i, the East-West Center, the Maui County government, the U.S. Soil Conservation Service and the U.S. Geological Survey. The Task Force should seek ways to coordinate the development and use of funds and government resources for Kaho'olawe watershed activities.

Recommendation Four A comprehensive examination and evaluation of the U.S. Navy's program for resource management and soil conservation and the Navy's land use activities on Kaho'olawe must be undertaken, as specified in the Consent Decree. As specified in the same Decree, appropriate modifications must be made if found to be in conflict with overall land stabilization goals.

Recommendation Five. A comprehensive examination and evaluation should be undertaken of the State Forestry program, particularly in regards to the planting of tamarisk trees parallel to the direction of water flow in critical watersheds and planned in coordination with other conservation measures.

Recommendation Six. In keeping with mandated historic preservation directives, the pace of archaeological site stabilization through the control of water-induced soil erosion, must increase dramatically over the next few years if existing sites are to remain in tact. Cultural resource management must be a priority for all resource agencies on Kaho'olawe and site stabilization activities integrated with overall resource use management on Kaho'olawe. The State Historic Preservation Division and the U.S. Navy, working with the Protect Kaho'olawe 'Ohana, must immediately resume management activities including: (a) the completion of a new survey of sites to establish baseline conditions that have changed since 1980 and to serve as a guideline for site stabilization and (b) the immediate stabilization of some 8,000 acres of threatened archaeologically-rich land and individual sites on Kaho'olawe's eroding hardpan.

Overall findings speak to a positive water resource development potential for Kaho'olawe and confirm the possibilities of using indigenous water resources to revegetate and restore Kaho'olawe's watersheds. This study confirms the existence and characteristics of the water resource on Kaho'olawe, and is one small step in demonstrating its considerable potential.

INTRODUCTION

In its 1.5 million year existence, Kaho'olawe has experienced more environmental change associated with human land use than with any other single factor. The most damaging changes to Kaho'olawe have occurred in the last 150 years as a result of land uses such as grazing, military training, vehicular traffic and associated activities. The significant environmental change that has occurred on Kaho'olawe has altered the hydrologic cycle on the island, changing the balances between infiltration, ground water recharge, surface runoff, evaporation and precipitation.

This document reports the results of a study of the surface and ground water resources of Kaho'olawe, the first such study to have been undertaken since Harold Stearns' pioneering work conducted in 1939 (see Stearns, 1940). The study was directed toward the identification of the geometry and characteristics of the surface and ground water supply and toward the development of projects demonstrating Kaho'olawe's water resource development potential. To demonstrate the link between water and land management, portions of project work focused on the installation of soil and water conservation structures. The structures were used to demonstrate effective methods of stabilizing water-induced erosion processes and of establishing a medium for vegetation growth. Finally, project results were used to construct an overall plan for the management and development of water and land resources on Kaho'olawe within the framework of objectives identified for Kaho'olawe by the community and within the context of the resource management needs of the island itself.

The report that follows is organized into four major sections. The first section of this report (Chapters 1, 2 and 3) describes background information necessary to understand the context of the Kaho'olawe water resources investigation. A history of major land use actions affecting Kaho'olawe's environment is presented, describing the probable impact of these actions on the water resource environment. A description of the objectives and design of the study is also included. Chapter 3 contains a description of the physiography, climate, soils and geology of Kaho'olawe, providing a summary of previous studies supplemented with recent research discoveries.

Section Two (Chapters 4 and 5) presents the results of the investigation of surface and ground water resources of Kaho'olawe, presenting the first recorded precipitation and streamflow data for Kaho'olawe resulting from storms occurring during the course of the study.

Section Three (Chapter 6) describes the results and implications of the project's soil and water conservation activities. Mechanisms for gully development and solutions for gully control are described.

Finally, Section Four (Chapters 7, 8 and 9) synthesizes the information collected during the study and identifies the major water resource needs of Kaho'olawe and the potential sources of water to meet demand. Estimated costs for water development are presented. The study concludes by proposing a water resource development and management plan for Kaho'olawe.

SECTION ONE

Background, Context and History of the Kaho'olawe Water Resources Study

Chapter 1

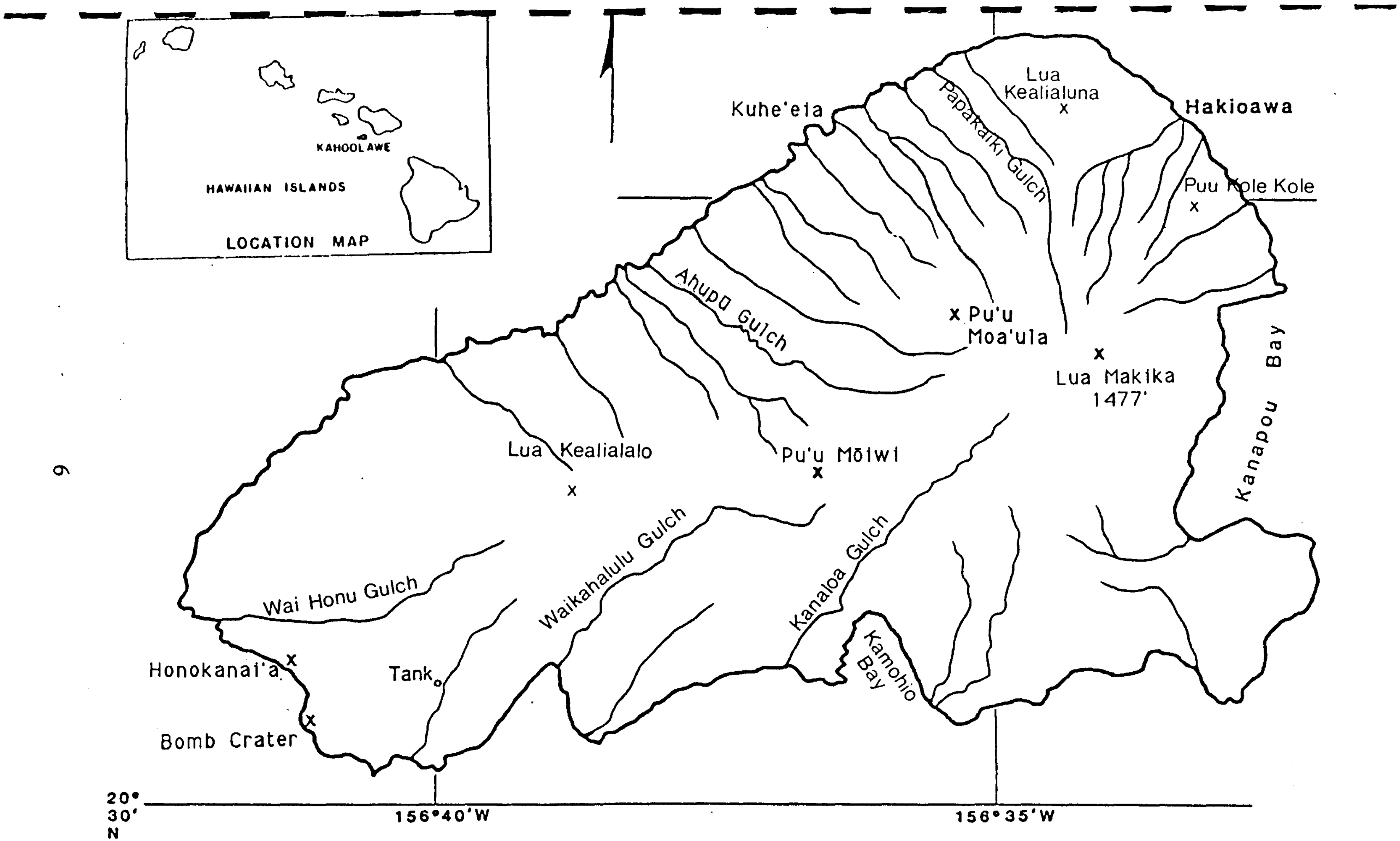
Environmental, Institutional and Historical Background

Introduction

There are three major components necessary to understand the background, context and need for the Kaho'olawe water resources study. First, the land base itself has undergone significant human-induced environmental change in the last 150 years that has literally destabilized the soil, water and vegetation base. It is important to understand these changes as they indicate the resource management strategies necessary to correct the problems and enhance the existing resource potential of Kaho'olawe. Moreover, the present environmental degradation threatens archaeological sites and the surrounding marine environment. Control of the soil erosion wrought by this dramatic environmental change will pose significant cost increases for future resource management programs unless the level of effort to stabilize the environment and archaeological sites is increased significantly within the next few years.

Second, there is significant legal, policy, and programmatic activity surrounding the use and management of Kaho'olawe's resources. Since 1900, there have been several Territorial and later State legislative resolutions and programs to manage and preserve the resources of Kaho'olawe. The federal government currently maintains primary responsibility for the management of Kaho'olawe's natural resources. The County of Maui has adopted a community plan for Kaho'olawe which outlines steps to preserve the island as a cultural park. Thus, there is significant legal precedence for, and government interest in, action on Kaho'olawe's behalf. That Kaho'olawe's environment continues to deteriorate despite this activity signals a need to coordinate agency activities to utilize the available resources in the most effective and efficient manner possible.

Third, there is significant local concern with the present use and management of the island's resources. Past and present community protests against further military use of Kaho'olawe have resulted in increased Navy resource management activity. The most recent community initiative has come from the Protect Kaho'olawe 'Ohana, a community based Native Hawaiian organization dedicated to the cultural preservation and use of the island. The 'Ohana is recognized as a party to resource management on Kaho'olawe through regular review of the Consent Decree's provisions. To supplement the State and Navy conservation programs, the Protect Kaho'olawe Fund/'Ohana successfully lobbied for a $75,000 legislative appropriation in 1986 for the present water resources study.[1] Hence community activity is a major factor in considering Kaho'olawe resource uses.



Scale: 1 inch = 1.4 miles

Figure 1.1. Map of Kaho'olawe showing major streams and features. Many small drainages are not included in this map. (Modified after Stearns, 1939).

Finally, an overview of the island's history is provided through the examination of each of the three aforementioned contextual sections. The history includes information from the latest archaeological studies on Kaho'olawe and recently discovered historical sources. The result is a new assessment of the island's environmental condition from the past to the present, essential to provide a foundation for future management efforts.

Together these components form the basis and context for water-resource related work on Kaho'olawe, and is described in more detail below. Any action involving natural resources on Kaho'olawe necessarily results in consultation with state, federal and local agencies, as well as Native Hawaiian groups and other community organizations. Thus, an understanding of the jurisdictional, institutional, environmental and resource management context will facilitate effective resource management activities on Kaho'olawe.

Environmental Changes on Kaho'olawe

Descriptions of Kaho'olawe are derived from historical accounts, archaeological data, and archaeobotanical information obtained from several major studies and accounts of Kaho'olawe.[2] Although a comprehensive review of these documents is beyond the scope of this discussion, certain key components relevant to the condition of Kaho'olawe's environment are discussed.

Vegetation

The earliest written descriptions of Kaho'olawe begin around the year 1779, and consist of accounts describing Kaho'olawe from aboard the passing ships of western explorers. Inasmuch as ships passed primarily along the south and western shores of Kaho'olawe, little was observed of the inland communities, now known to have existed primarily in the central, north and eastern portions of the island.[3] Reports of a barren, sandy and treeless island must therefore be seen as descriptions of the arid west and sheer cliff-lined southern portions of Kaho'olawe.

These reports also must be balanced against archaeobotanical and stratigraphic information which confirm the presence of a diverse dryland forest similar in species composition to the remnant forests of Pu'uwa'awa'a, on the island of Hawai'i, and Kanepu'u on Lana'i (Allen, 1987). Judging from the approximately 10,000 fireplaces found on Kaho'olawe during the 1976-80 archaeological survey various woody species were available in pre-haole occupation.[4] Analyses from a few of these fireplaces have identified 18 taxa, with an additional 31 unidentified taxa (Murakami, 1987). The dry westward portion of the island may have had much more open vegetation, dominated by grassland and shrub.

Settlement of Kaho'olawe's inland plateau and its use for agriculture, may have led to a gradual change from forest to a savanna type vegetation, maintained by regular burning and a reduction of fallow periods. Burning would have encouraged growth of pili grass which could have been used as an agricultural mulch (Spriggs, 1987:I-48). Based upon archaeological studies, the transition to predominant grassland appears to have occurred sometime in the 18th century. How complete this vegetation clearance was is difficult to establish based on current evidence, but pockets of dryland forest appear to have survived into the early historic period. This savanna condition is described in the first written accounts of visits to Kaho'olawe in the 1850's.

In 1857 Maui Governor Nahaolelua and Ioane Richardson conducted a brief survey of the island for Lot Kamehameha (V) to determine a fair rental value for Kaho'olawe. They report the following:

> The grass growing at the seashore are the kalamalo and the grass for thatching houses [probably pili] which grow plentiful there, and other things that properly grow on the dry seashores, and some weeds with thorns, which grow during the rainy seasons on the kula near the seashore and called umealu (Fox-tail). On the mountains, the kalamalo is the grass that grows most, and there was also some grass for thatching houses, and in some places of the mountains, the kukaepua'a grass was also growing, and there was quite a spread of kikania horse feed, and a few pualele (sow-thistle).
>
> Of the trees on the mountains, there are no large trees on the mountains, there are growing akoko trees, low, not more than 4 feet high, and there are some small a'ali'i trees, very few, and small sandalwood, and there are some other small trees, a few, and on the kula some small wiliwili trees, and they are few (Nahaolelua and Richardson, 1857).

In June 1859, William Webster, government land agent estimated that Kaho'olawe had sufficient pasturage for 10,000 sheep and 5,000 goats. He reports:

> On the summit of the Island there is about four or five thousand acres of land where I should suppose from its appearance the feed was sufficiently green throughout the year to support sheep without water. About half of this land is at present covered with a scrubby brittle succulent plant called 'akoko.'
>
> ...The best tract of sheep land...extends for 5 or 6 miles along the weather side from the southern end of the high cliffs southward--this is beautiful for sheep...undulating with sweet herbage and altogether free from scrub (Webster, 1859).

Webster suggested that cattle be introduced to clear the akoko (*Euphorbia*).

The only description of damage to Kaho'olawe's vegetation is mentioned in 1854 by Perkins.

> At one place was passed what had once been a grove of akokoa [sic] trees, but nothing now remained save an area covered by withered trunks and branches, bleached as white as skeletons in the sun, the bark having been stripped from them by the goats (in Spriggs, 1987:I-38)

There is no mention of barren areas or eroded slopes in any of the early 1850 descriptions of Kaho'olawe's inland plateau, before the introduction of livestock. This same area today is now largely eroded hardpan devoid of vegetation.

Two early accounts of Kaho'olawe by Wilkes and Perkins have been used to suggest that aeolian erosion was already underway on the island at the time. However, Spriggs (1987) explains that these descriptions were of the western end of the island, the driest part with less than 10 inches of rainfall each year, an area of shrubs, and at best, annual grassland. "Without sufficient rainfall," he notes, "the grass would have died back revealing the underlying soil, but not necessarily representing an eroded landscape (Spriggs, 1987:I-6).

There is no evidence to suggest resource abuse by Native Hawaiian inhabitants of the island nor that their actions caused large-scale soil erosion through uncontrolled burning. This theory of pre-haole erosion was developed by archaeologist Robert Hommon (1980b) in studies from the 1976-80 archaeological survey of Kaho'olawe. A new archaeological study conducted on Kaho'olawe in 1982-83 generated new theories regarding the origins of erosion on the island. A careful review of the original stratigraphic data conducted by archaeologist Matthew Spriggs thoroughly repudiates Hommon's pre-haole erosion theory. Spriggs concludes that fire was used to clear forested lands for agriculture, and high winds may have occasionally spread fires as they do today, however, the theories suggesting pre-haole destruction of Kaho'olawe's environment are incorrect. It is unfortunate that these theories continue to be cited in important scholarly works despite sound scientific evidence to the contrary.[5]

With the use of Kaho'olawe as a ranch, the goats and other livestock ate the vegetation and trampled soils (with the heaviest use from 1859-1910 and 1918-1941), high winds carried soils away, diminishing the medium for vegetative growth. Mangenot describes the effects worldwide of introduced grazing animals which also applies to Kaho'olawe.

> The cutting hoofs of sheep and goats chop the herbs and small shrubs; the heavier cows trample them. Grazing and browsing affect each plant according to its organization: poorly rooted herbs are pulled by the roots; those having a strong root system are mutilated but remain;

> small trees are sheared more or less regularly according to the size and attitude of the animal (in Spriggs, 1987:I-42).

Kiawe (*Prosopis pallida*), introduced sometime during the first ranching period, was able to quickly spread, further robbing near surface soils of moisture that previously supported grasses and shrubs. Other exotic plant cover, like Australian saltbush (*Atriplex senibaccata*) and spineless cactus were introduced by the ranchers to prevent soil erosion. Table 1.1 at the end of this chapter contains a chronology of events and land use practices that led to the gradual decline in the vegetative cover of Kaho'olawe.

Soil

Evidence of extensive soil development on Kaho'olawe is present in the stratigraphic record of the island and is obtained from pit excavations, observations of exposed soils in gully walls and from near-shore bottom sediment cores of the island's major drainages (Stearns, 1939; Spriggs, 1987; Hommon, 1980b and Environmental Impact Statement Corporation, 1977).

Much of the soil originally derived from the weathering of the parent material (olivine and alkalic basalts, discussed in Chapter 3) on Kaho'olawe would, given vegetation cover, have excellent water holding capacities equivalent to a silt-loam soil type. These soils would also tend to maximize infiltration and deep percolation, hence would be capable of supporting the dry forest vegetation type and limited agriculture activities inferred from archaeological studies and historical accounts of Kaho'olawe.

William F. Allen, sent to the island in 1858 on an exploratory expedition for the new leaseholders of Kaho'olawe reports:

> In the centre of the northern part, is a mound which is the highest point of land on the Island, about this the soil is very good being a sort of loom, here natives have some sugar cane growing; melons, potatoes and pumpkins grow well here (Silva, 1983:54).

As mentioned, the use of Kaho'olawe for ranching resulted in a loss of vegetative cover and a trampling of soils. Once exposed, the particular soil types on the island became extremely vulnerable to wind and water erosion.[6]

The first report of large scale erosion on Kaho'olawe is made in 1880 based on information from Walter Murray Gibson.

> It was at one time a flourishing sheep ranch, owned by Judge Elisha H. Allen, but owing to being overstocked and severe droughts the land became utterly denuded of vegetation, and the constant violent

> tradewinds blowing over its unprotected plain have been for years carrying off the loosened soil in red clouds of dust, that are blown 30 or 40 miles out to sea. When visited in 1879 not a sheep was to be seen on the plains... Of the surface about 35,000 acres is an utter unreclaimable desert, and there are about 5000 acres of good pasture land in the western, or lee side of the island (Bowser, 1880:576).

Gibson's account of the eroded acreage is certainly exaggerated and the number of sheep assessed at the time of his visit was nearly 2,000. However, placed in the context of other historical descriptions of the island's environment, Gibson's report helps to mark the occurrence of large scale eolian erosion processes on Kaho'olawe at sometime between 1876 to 1879, soon after the introduction of thousands of sheep to the island (Spriggs, 1987:I-11).

In response to the erosion problem on Kaho'olawe, ranchers Courtney and Cummings in 1881 began planting efforts to stabilize soils. From 1903 onwards, reports of soil erosion on Kaho'olawe were widely reported in newspapers.[7] When damage to Kaho'olawe became evident, steps were taken to begin eradication of all cloven-hoofed animals from the island. This was one of several conditions of rancher Angus McPhee's lease in 1919.

It is clear that Kaho'olawe's soils were damaged by the removal of vegetation and trampling by livestock. By 1940, the soils would have been considered fragile. Despite the island's denuded state at the end of the ranching period, the island still showed promise for recovery. Geologist Harold Stearns described the island's eroded hardpan area as still relatively undissected by gullies in 1939. He writes: "It is likely that if cattle were kept off this area for 5 to 10 years, it would be reclaimed and become the most valuable grazing land on the island."[8]

Military activity began on Kaho'olawe as early as 1939, but heavy use began in 1941, when the U.S. military assumed control over the island, evicting the ranch lessees in the process. All land management activities ceased with Army control over Kaho'olawe. The wild sheep and goat population was no longer controlled and increased accelerating the loss of vegetative cover.[9]

The island was used for target practice by the U.S. military, with use of live, 1,000-pound or greater ordnance. The remaining stability of Kaho'olawe's soils was negatively impacted as a result of heavy shelling and vehicular traffic. As a result of detonation of ordnance, soils were shattered and made more vulnerable to both wind and water erosion. Fires caused by ordnance detonation and flares removed remaining stands of vegetation. Road construction and uncontrolled vehicular traffic in all but the most remote places of Kaho'olawe further exacerbated runoff and wind erosion processes.

At present, much of the central and eastern portion of Kaho'olawe contains little soil cover, with much of the "hardpan" surface considered to be the "B" horizon of Kaho'olawe's original soils.[10] Figure 1.2 presents a map of the soil conditions as described by Stearns in 1939.

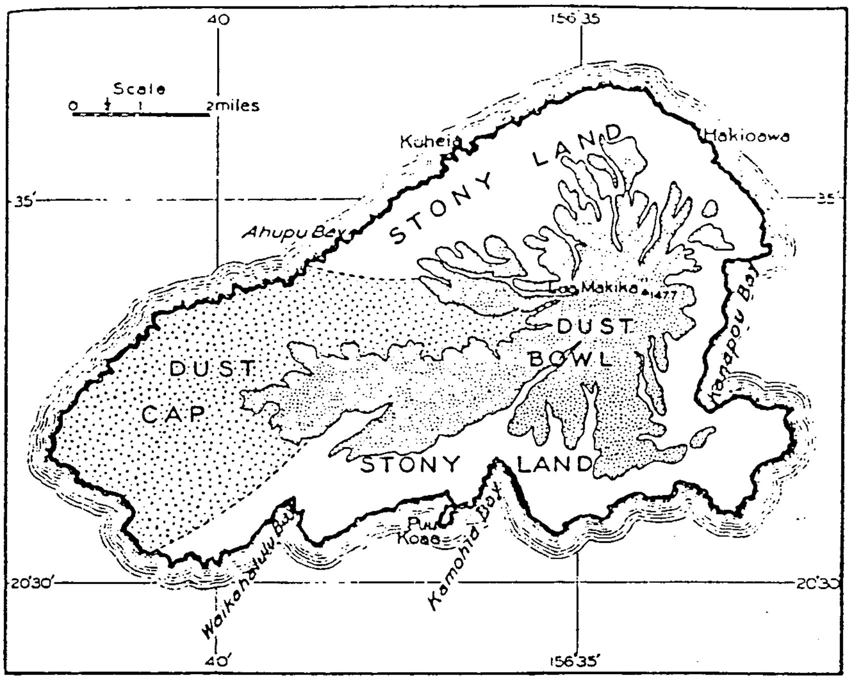


Figure 1.2. Map of Kaho'olawe showing the condition of the land surface as delineated by Harold Stearns (1940). Note the location of the "dust bowl," considered prime pasture land in 1850. Today this same surface is largely unvegetated, eroded hardpan.

Water

Because there is no indication of permanent streams on Kaho'olawe, early uses of water on the island consisted of the use of springs, dug wells and terraces strategically placed to take advantage of natural runoff. Reports of springs on Kaho'olawe are found in traditional Hawaiian chants, newspaper articles, and books describing the life of island residents.[11] Stearns measured the discharge of a spring at Kanapou Bay in March, 1939 at 1 pint per minute. The existence and use of basal ground water on Kaho'olawe is identified through descriptions of seven hand-dug wells on Kaho'olawe (Stearns, 1940; McAllister, 1933). Wells were constructed and used by both Native Hawaiian inhabitants and later by non-Hawaiian residents of the island. The three traditional wells are located at Kanapou, Hakioawa, Ahupu and possibly another at Waikahalulu.

It is interesting to note the ancient Hawaiian inhabitants demonstrated superior technical skill and knowledge compared to non-native residents in locating their wells on Kaho'olawe. Stearns reported that Hawaiians located their wells next to the walls of gulches, where they tapped water from basalt, while Westerners dug their wells straight down into the alluvium.

> Moreover, the alluvium consists of boulders imbedded in fine silt that has low permeability. Water moves more freely from inland through basalt, and hence the Hawaiian wells were better located than those sunk by white men (Stearns, 1940, p. 130).

Kaho'olawe's present appearance as a water-poor island contrasts sharply with these historical descriptions of water use, especially with regard to the presence of springs. As an explanation for this change in water resource condition, it seems plausible to suggest that in the past, a thick soil and vegetative cover, which permitted infiltration, also enhanced the development of perched water bodies capable of sustaining spring discharge on Kaho'olawe. Recharge to the basal lens was also likely. Surface water runoff would therefore be only a fraction of the quantity of runoff today.

According to investigations by Stearns, ground water (basal) on Kaho'olawe was considered drinkable (non-saline) until about 1920.

> The equipment found and reports of visitors to the island seem to indicate that the wells in Ahupu and Hakioawa gulches yielded water suitable for stock until about 1900. E.P. Low states that when he leased the island on December 28, 1906, these wells yielded potable water for stock except during dry months. Angus McPhee reports that he drank potable water from Ahupu well about 1917. It appears that about 50 Hawaiians obtained drinking water from wells in these gulches during historic time, and that the Kynnersleys likewise pumped water for stock from the wells they dug in the same gulches while they leased the island [from 1887-1901]. Thus, there has been apparently a progressive decrease in the quantity of ground water in the gulches, until by 1919 no water potable for stock remained (Stearns, 1940:131).

The increased salinity of basal ground water and depletion of perched water correlates well with the 1920 ranch program to expand the kiawe forests on Kaho'olawe (kiawe beans were considered excellent cattlefeed).

> The spread of the kiawe tree is coincident with the decrease in the fresh ground water supply. It may be that they consume by transpiration much of the rain water that formerly percolated to the zone of saturation and supplied these wells. Thick stands of these trees cover the gulch floors and doubtless rob the zone of saturation of most of the fresh water that reaches the water table in the vicinity of the wells. These trees are now green throughout the year by subirrigation (Stearns, 1940:131).

Surface waters were also used historically: water remaining for six months or more in Kealialalo and Kealialuna craters and pools of water remaining after rain in the many gulches on the island. Spriggs (1987) also cites archaeologist Kenneth Emory's descriptions of water collection on neighboring Lana'i, methods which could have been used on Kaho'olawe as well. On the inland plateau of Lana'i, residents collected dew from the surrounding shrubbery. Oiled tapa was also used, spread on the ground to collect the dew. In recent years, members of the Protect Kaho'olawe 'Ohana have reported their sleeping bags became soaked by moisture from the night air after overnight stays at Kaho'olawe's summit, providing additional evidence that fog drip and dew may have been an important water source for Native residents as well as for the island's vegetation.[12]

Surface water was used extensively during the later ranch period from 1919 to 1940. Conditional lease requirements imposed by the Territory required the Kaho'olawe Ranch to install a water supply system. The ranch built extensive water catchment systems for both rainfall and runoff. Stearns described several structures, including roof catchments and runoff diversion structures that could capture and store over 1,000,000 gallons of water.[13]

Land and Water Use and the Present Environment

The relationship between land use and the water resource is dramatically illustrated by the way in which increased soil erosion altered the quantity and quality of ground water and quantity and characteristics of surface water on Kaho'olawe. The destruction of vegetation cover and consequent removal of the soil cover by wind erosion reduced infiltration and deep percolation and therefore increased runoff. Recharge to ground water, and thus spring discharge, was markedly reduced. Existing ground water resources are diminished and become saline as a result of reduced fresh water recharge coupled with the introduction of the phreatophyte kiawe. Increased high-velocity runoff, combined with severely unstable soils, imparted a high sediment content to runoff. Diversion structures designed to harvest this runoff then filled and became useless and costly to maintain as a result of sediment build up.

These striking examples of the impact of land use on water resources have occurred faster on Kaho'olawe as a result of exceedingly destructive land use activities in a fragile island environment. However, signs of similar processes and impacts are not unusual in the Hawaiian islands.

Government Legislation and Programmatic Activities on Kaho'olawe, 1850-Present

The island of Kaho'olawe had been used by Native Hawaiians for a considerable length of time prior to occupation by foreigners (900-1800 A.D.)

Archaeological and demographic research suggests the island sustained a population between 725 - 1,125.[14] The large number of Hawaiian place names for the small island provides corroborative evidence that traditional use of Kaho'olawe was extensive. As discussed in previous sections, evidence of erosion does not appear until western land use of the island occurs. It is likely that resource management practices adopted by island inhabitants would have had the same characteristics and same stewardship functions as activities practiced by Hawaiians on other islands (Kelly, 1989).

Court records indicate Kaho'olawe was cited on occasion as a place of banishment for criminal offenders. However, serious governmental interest in the use of Kaho'olawe began in 1857 when Lot Kamehameha (V) then King, ordered a survey be made of the island to determine a fair rental value soon after western government advisers succeeded in instituting a system of private land ownership and use. The land was considered attractive for ranching because lessees could avoid the cost of erecting and maintaining extensive fencing, often necessary on other islands.

In 1858, the government issued a lease for Kaho'olawe to private individuals for stock purposes. The lease was awarded to Elisha A. Allen (then Hawai'i's Chief Justice) and Robert C. Wyllie (then the Minister of Foreign Affairs). Allen and Wyllie were issued the lease although a number of petitions were submitted to the government for lease and purchase of Kaho'olawe from 1847 to 1857. It appears Wyllie's influence as a part of the King's Privy Council and Allen's high judicial post assured the award over other requests. Thus, Kaho'olawe was not overlooked in the post-Mahele movement by haole elites to acquire large tracts of Hawaiian land. The lease for Kaho'olawe was to remain under haole ownership, as did most land in Hawai'i with any considered commercial value.[15]

Ranch use continued under several different lessees into the territorial period through 1910. The lease remained intact through the illegal overthrow of the Hawaiian government and the eventual annexation of Hawai'i to the United States. Designated as government lands in 1848 during the Mahele (the division of lands which instituted private title in Hawai'i) Kaho'olawe became part of the lands "ceded" to the U.S. upon annexation and remains a part of the ceded land trust today.[16]

A growing concern over the scale of soil erosion on the island created by ranching sparked the Governor of the Territory of Hawai'i, Walter Frear, to declare Kaho'olawe a forest reserve in 1910. Superintendent of Forestry, Ralph S. Hosmer wrote at the time:

> On general principles, it is evident that in a community believing in conservation, such waste as is now going on an island that was formerly as productive as was Kaho'olawe, ought to be stopped. As erosion continues, the island becomes of less and less value to the

people of the Territory, whereas were Kaho'olawe to be effectively reclaimed it could in time again be made to be a valuable asset (in Silva, 1983:80)

Governor Frear envisioned Kaho'olawe would be used for a world-class conservation experiment to test the emerging conservation theory linking forest cover and rainfall. He is quoted in the Maui News:

> Kaho'olawe is now perfectly bare of trees and shrubs. When the lease is up, which will be shortly, we can remove all of the livestock and plant the island with trees and shrubs in hopes that they will clothe the island, as it was clothed in former times, with luxuriant forests. Then, be keeping a record of the rainfall over a period of years, a demonstration will be made that perhaps will be conclusive on the question at issue (in Silva, 1983:78-79).

To support these plans Frear called upon the U.S. Congress "to make an appropriation for the work in Hawai'i equal to that of the local legislature (Silva, 1983:78).

The premise behind the Kaho'olawe experiments focused on the popular belief at that time that rainfall had decreased on Kaho'olawe as a direct result of the loss of forest cover due to overgrazing. These opinions, Spriggs (1987) points out, assume incorrectly that prior to ranching there was forest on the island, which as has been noted, was not the case by 1850.[17]

Because the erosion problems were linked to overgrazing by both domestic and feral animals, the Territory required then leaseholder Eben Low, also owner of O'ahu Shipping Company, to remove his sheep and eradicate the island's goats for the remission of his remaining lease rent. Forestry Superintendent Hosmer had no illusions about the difficulty in removing livestock from the island and saw the project as being long-term in scope. He was also concerned that the reclamation efforts involve comprehensive planning, technical research and study.

> Should the artificial restoration of vegetation on Kaho'olawe come later to be undertaken, it should be as the result of a comprehensive and systematic study of the problem, embodied in a detailed plan for planting. It is unnecessary to discuss this matter here further than to say again that the first step in any plan must necessarily be the total removal from the island of all cattle, sheep and goats. The reclamation of Kaho'olawe will be anything but an easy task but I believe it is possible.
>
> ...even though nothing more is done for some years than completely to remove the stock now thereon, the condition of the island can not but improve. Further, if set apart as a forest reserve, it will be ready for

whatever other program of improvement may in the future seem desirable.

Pursuant to Hosmer's remarks, a series of visits were made to Kaho'olawe during the forest reserve period by visiting and resident scholars, including a team from the Bishop Museum. The first archaeological survey of Kaho'olawe was conducted by J.F.G. Stokes on the Bishop Museum trip. Stokes returned to the island later leaving with a small inventory of artifacts, some quite unique to the island.[18]

Given the available resources and hunting technology (rifle on horseback), the Territorial government met with only moderate success at eliminating the goats and sheep on the island. Charles S. Judd, who replaced Hosmer as Territorial Forestry Superintendent reported that approximately 150 sheep and 4,300 goats were slaughtered. He described a definite improvement in the environment, with the return of vegetation, but states that funding for the project was sorely lacking. Reforestation efforts on the island were never entirely successful, with only 32 out of 372 ironwood and eucalyptus trees surviving (Silva, 1987:77&104).

During WWI, there occurred an acute shortage of available meat in the islands which created greater pressure for the Territory to open up pasture land for cattle and find new local sources of meat.[19] A program was started by the Territorial Food Commission to identify Forest Service lands available for cattle raising. As an interim measure, the Territory ordered that all goats slaughtered on Kaho'olawe be removed and sold for local consumption. This resulted in slowing eradication efforts.

Eventually, in response to the problem of rising meat costs and with the encouragement of former leaseholder Eben Low, the Territory decided to lease the island once again in 1918 to private individuals for cattle grazing. Low argued that the kiawe beans found on the island provided an excellent form of cattlefeed and encouraged the Territory to pursue expansion of the kiawe forests through seeding.[20] Low also introduced cactus (*Opuntia magacantha* & *Nopalea cochenillifera*) to the island for use as cattlefeed during this time.

With the issuance of a new ranching lease it was hoped that private individuals, under strict conditional ranch use, could accomplish the resource management goals of the Territory as well as provide a new affordable source of beef for local consumption. Angus McPhee was awarded the new lease and began efforts to eradicate the goats and sheep, install a new water supply system, and revegetate the denuded hardpan. A limited number of cattle and horses were permitted by the lease. The pasturing of horses was permitted to encourage the spread of the kiawe forests. Grazing continued until 1941.

Rancher MacPhee was forcibly evicted from Kaho'olawe in 1941 when the U.S. military assumed jurisdiction over the island. All land management efforts ceased. Just six years before Hawai'i's statehood, in 1953, President Eisenhower signed Executive Order 10436, reserving Kaho'olawe for military use. During the period of military use, the Territorial and subsequently, the State legislatures have expressed numerous times its intention to have Kaho'olawe returned to the jurisdiction of the people of Hawai'i for civilian use. The first attempt was made in 1947, followed by others in 1953, 1969, 1977, 1984 and 1988.[21] Most of this activity was a response to community objections against further military use of the island.

From 1965 objections were raised regularly by numerous public officials to end military use of Kaho'olawe. In response to this renewed interest in the island, the State Department of Land and Natural Resources in 1969 considered developing a conservation program for Kaho'olawe. After a visit to the island by DLNR personnel, a memorandum addressed to the Chairman of the Board of Land and Natural Resources, concludes:

> ...(there is) clear indication that little or no conservation measures are being taken on Kaho'olawe... The animal population is completely out of control. Soil conservation is non-existent in a large area, and other sections of the island are rapidly deteriorating. There is sufficient evidence to show that with a proper conservation program soil erosion can be checked (in Silva 1983:301).

In cooperation with the U.S. Forest Service, U.S. Soil Conservation Service and with assistance from the U.S. Navy, the State conducted experimental planting trials on Kaho'olawe in 1971. Several planting enclosures were established using various plant species suitable to the conditions on Kaho'olawe. Highly dependent on the quantity of rainfall in a given year, State and local experimental planting efforts met with mixed success (Whitesell, 1971; Whitesell and Wong 1972, 1974).

The 1977 Legislative Study, Kaho'olawe Aloha No, was a benchmark policy document for the State which directed State resources toward the island's recovery. Meant to serve as an independent study on the island's use, the report questioned continued Navy activity on Kaho'olawe. Recommendations identified programs for State participation, including support for the recently begun archaeological survey of the island and further conservation work. The report also recommended the establishment of a coordination committee to work with the Navy to develop programs for the island. Public input to the committee was emphasized.

Pursuant to the study recommendations, the State executed a Memorandum of Understanding in 1978 with the Navy to implement a soil and water conservation program. Although community members from the Protect Kaho'olawe 'Ohana were parties to the negotiations for the Memorandum, they were not signatories. However, the Memorandum did recognize community interest in the management and use of Kaho'olawe. Soon after the development of the agreement, the State designed an overall soil erosion plan on Kaho'olawe (Wong, 1978). The plan called for the development of check dams to control soil erosion, tree windbreak plantings, community native revegetation projects, and goat eradication.

Pursuant to the Memorandum of Understanding, a tamarisk tree planting effort was conducted jointly by the State and the Navy. Initiated in 1979, the tamarisk planting methodology called for the directional detonation of ordnance to plant the trees as wind breaks in rows several hundred feet long with 250 to 300 feet between rows. As of December 1988, over 50,000 holes have been detonated and slightly over 36,000 trees planted. The tamarisk trees, planted perpendicular to the prevailing wind direction and occasionally lined up with existing gullies, have succeeded in reducing wind velocities and have consequently permitted the limited growth of Australian saltbush (*Atriplex senibaccata*) in between tree lines. However, the trees' overall impact on water flow and gully development remains problematic.[22]

In December 1980, the Navy and the Protect Kaho'olawe 'Ohana signed a negotiated agreement as a result of a civil suit filed in 1976 (U.S. District Court of Hawai'i Civil No. 76-0380). Provisions of the Consent Decree required the Navy to implement an erosion control plan, restrict and monitor military training activities, eradicate the feral goat population and implement an archaeological management plan.

Despite the list of conservation activities presented, little success has been achieved in controlling the loss of soil and archaeological sites on Kaho'olawe as a result of water-induced erosion. A 1987 report summarizing conservation activities on Kaho'olawe concluded that current conservation efforts are ineffective and cannot match the scale of erosion problems on the island (Protect Kaho'olawe 'Ohana, 1987). Moreover, field inspection of existing check dams revealed their overwhelming ineffectiveness in arresting gully formation and headcut advancement.[23]

Like the windbreak program, Navy-assisted planting efforts have been hindered because hydrological factors were not taken into consideration. For instance, the site preparation for a trial native planting project in 1985 involved the scarification of the ground parallel to the flow of water causing the formation of little rivulets through the site. The evidence suggests the need for the development of integrative conservation strategies which address all the active erosion agents on the island. In addition, there is a need for comprehensive planning for greater coordination between all the resource management parties.

In 1981, the entire island of Kaho'olawe was listed on the National Register of Historic Places as a result of the discovery of over 500 sites and 2,000 features of cultural significance on the island. During the inventory of archaeological sites, it was revealed that many of the sites were damaged by military training activities. A review of the archaeological site forms for Kaho'olawe provide proof of the extent of site destabilization caused by military activities.[24] At the present time, many archaeological sites are threatened by water-induced erosion (sheet flow). The density of sites on the "hardpan" area appears to have been severely reduced in just 8 years since the island's listing on the National Register of Historic Places.

Maui County, in whose jurisdiction Kaho'olawe lies, has also expressed concern for Kaho'olawe's resource management. In 1982, the County adopted a community plan for the island of Kaho'olawe. The plan development attracted substantial community participation, particularly from members of the Protect Kaho'olawe 'Ohana. The plan was drafted with the participation of the former Governor of Hawai'i, John Waihee (EDAW, Inc. 1982). The plan outlined the future direction of land use for Kaho'olawe and identified specific activities necessary to achieve this end, including:

- designation of several thousand acres on Kaho'olawe for scientific, cultural, religious and educational activities alone,
- establishment of several permanent and temporary base camps,
- continued development of hiking trails for visitors,
- development of programs to protect archaeological sites,
- gradual reduction in military training sites and targets,
- continued ordnance clearing in preparation for the return of Kaho'olawe to the State of Hawai'i
- development of a revegetation plan, and
- conduct a comprehensive water resources study of Kaho'olawe.

Proper management of Kaho'olawe is clearly mandated legally through several agreements and orders. In addition, various governmental bodies have developed policies, plans and programs to this end in anticipation of the island's eventual return to the State of Hawai'i for public use. Moreover, concern for Kaho'olawe's environmental deterioration has existed since the occurrence of large scale erosion in the late 19th century. The expression and desire for the island's recovery is reflected in this record of institutional activity.

Community Efforts and Strategies

Concern for the management of Kaho'olawe's natural and cultural resources has been expressed by several major community initiatives in the last 20 years. These efforts are important because they signal the community's opinion regarding land use on Kaho'olawe and because community efforts have long been the primary stimulator of resource management activities on behalf of Kaho'olawe.

From 1965 to 1969 Navy bombing practices began to create an uproar of complaints from a burgeoning Maui island population, particularly in the areas of Makena, Lahaina and Kula due to the noise and tremors which occur during training maneuvers. After receiving little cooperation from the Navy regarding the complaints, Maui Mayor Elmer Carvalho, in 1969 spearheaded a campaign to seek greater control over Kaho'olawe and end military activity on the island. Carvalho pressed the issue further, by charging the Navy with non-compliance in executing the provisions of Executive Order 10493, which gave the Navy formal jurisdiction over Kaho'olawe. The Order provided the Navy conduct certain land management programs on the island and stipulated the eventual return of the island to the State in habitable condition when it was no longer needed for military use. Carvalho pressed for the Navy to begin long neglected conservation activities. He solicited the assistance of Hawai'i's Congressional delegation in this effort and garnered their full support to stop further military use of Kaho'olawe. The delegation at the time included Senator Hiram Fong, Representative Patsy Mink, Representative Spark Matsunaga and Senator Daniel Inouye.

The Navy responded to the political challenges by reaffirming Kaho'olawe's importance to military training and denied any responsibility for conservation work which it felt was solely a State responsibility.[25] Sparked by the protests, the Navy accommodated a trip to the island by the State Department of Land and Natural Resources to conduct a survey of the island and assess the potential for the development of a conservation program. Newspaper articles surrounding the controversy appeared regularly in the local papers. The furor over the island peaked when Mayor Carvalho found a 500 pound bomb on his property in Ma'alaea, Maui just 12 miles north of Kaho'olawe. Questions regarding the safety of Maui residents forced the issue of continued military use of Kaho'olawe to the forefront in the early 1970's.

Amid the growing discontent with the Navy, the Maui County Council sent resolutions to then President Nixon and the Navy calling for a halt to the bombing. In 1970 the Hawai'i Association of Soil and Water Conservation Districts sent a resolution to state and federal officials urging action on a conservation program for Kaho'olawe. Later that year, the State Department of Land and Natural Resources asked the Navy to cooperate in developing a conservation program for the island focusing on goat eradication and test plantings. The idea to develop Kaho'olawe into a cultural park was first raised that same year by Lt. Governor Tom Gill and Mayor Carvalho after a visit to the island.

In the mid-1970's activity over Kaho'olawe waned until 1976, when Native Hawaiians and many of their supporters began a series of occupations of Kaho'olawe over a period of 2 years in direct defiance of military prohibitions on public access. Numerous protesters were arrested for trespassing onto the island and some jailed. Led by a young Hawaiian, George Helm, the protests against the bombing of Kaho'olawe gripped the attention of the general public and government officials as no other series of protests in the modern period. The protests spilled over into a session of the 1977 State Legislature, where in an unprecedented move, the rules of the State House were suspended and Helm was invited to address the Legislature regarding the issue. This event gave rise to the 1977 State Legislative report on Kaho'olawe. Later that year, Helm along with Maui resident Kimo Mitchell, were lost at sea in an attempt to access the island.

The high price Hawaiians and their supporters were willing to pay for a largely uninhabited island must be understood in the context of a larger movement of Hawaiian discontent and cultural awakening which began in the 1970's. Acts of civil disobedience challenging the military use of Kaho'olawe was part of an emerging Hawaiian Movement, characterized by a new consciousness among modern Hawaiians about their history, their culture and their subjugation to western values and institutions, including capitalism, formal education, and Christianity (Trask, 1987).

Hawaiian scholar and activist Haunani-Kay Trask describes the significance of the Kaho'olawe protests for the Movement.

> For over fifteen years--from 1970 to 1985--Hawaiian discontent erupted in mass protests against land alienation and cultural destruction around the State. ...the political organizations began with a specific focus on the abuses of Hawaiian lands and Hawaiian people. With the birth of the Kaho'olawe 'Ohana in 1976, the discourse of protest expanded from a focus on land abuse to an argument for a positive alternative. Phrased in Hawaiian, this alternative of Aloha 'Aina (love of the land) signaled the merging of political protest with cultural assertion. Thus, Hawaiian communities did more than struggle against land development. They also argued for a preferred alternative to capitalism: Hawaiian land use ethics of preservation, conservation and respect for the sacredness of nature; and harmony between people, their culture and their environment. These ethics were taken directly from Hawaiian culture (Trask, 1987:167).

To many Hawaiians then, Kaho'olawe came to symbolize the cultural conflict between western and Hawaiian forms of land use, as well as the loss of Native control and access to a traditional land base. Trask describes the spiritual importance of the land for Hawaiians as:

> ...a serious search for the spiritual source of Hawaiian culture. As many young people journeyed back through a century and a half of colonial repression to the pre-haole sources of their culture, they discovered, with the help of their elders, that Hawaiian religion was rooted in a profound relationship to the land. Because Hawaiians took their sustenance from the land, their daily activities--planting, fishing, building, even eating--expressed spiritual as well as physical aspects of being. This understanding of life as a relationship between the spirit of the land and the people of the land, between material survival and cultural expression, between work and a respect for the wondrous and varied bounty of nature--all this shaped Hawaiian philosophy, music, art, dance, language, indeed, the daily rhythm of Hawaiian life. The gradual re-learning of this cultural heritage led activist Hawaiians to demand what their nineteenth century counterparts had gradually lost: a land base for the practice and transmission of their culture... (Trask, 1987:163).

In response to the series of arrests, members of the Protect Kaho'olawe Association (which later became known as the Protect Kaho'olawe 'Ohana) in 1976, sued the United States Secretaries of Defense and Navy over the military's misuse of island resources and for abridging the rights of Native Hawaiians to practice their religion. Four years after the original suit was filed, the U.S. District Court issued a Consent Decree determining the rights of the parties, which included granting the 'Ohana access to Kaho'olawe for religious, cultural, scientific and educational purposes.[26] The Decree also restricted the Navy's target zone to the central third of the island and limited the size and quantity of live ordnance that could be used for training. An additional result of the 'Ohana's legal action was the nomination and designation of the entire island of Kaho'olawe to the National Register of Historic Places in 1981.[27]

An important component of the Consent Decree is the specification of a land management plan which imposes certain legal responsibilities on the U.S. Navy and the 'Ohana regarding the management of the island's resources (U.S. District Court of Hawai'i Civil No. 76-0380). Moreover, the 'Ohana was legally recognized and given institutional standing in resource management issues affecting Kaho'olawe. The Navy and the 'Ohana now meet regularly to review and evaluate the progress of natural and cultural resource management programs for the island.

To supplement the Navy programs, the 'Ohana in 1986, succeeded in obtaining State funding for a water resources study of Kaho'olawe. Following the release of funds in 1988, the 'Ohana moved quickly to involve the U.S. Geological Survey and to enlist the services of a water resources consultant. The project results as described herein provide a framework for the orderly development and management of the land and water resources of Kaho'olawe.

The cultural use and significance of Kaho'olawe raised by the Protect Kaho'olawe 'Ohana is essential to the study of the island because of its impact on shaping future land use, policies and programs. Moreover, as part of the ceded lands trust, Kaho'olawe cannot be ignored in discussions regarding Hawaiian reparations for the United States' illegal overthrow of the Hawaiian Kingdom and the loss of Hawaiian sovereignty.

Summary

This chapter has provided background material relevant to the study and management of water resources on Kaho'olawe. A review of the material presented reveals the institutional, legal, political and natural resource management context in which activities on Kaho'olawe must proceed. After many years of neglect, the resource problems on Kaho'olawe and community concerns have finally forced more serious and higher-level attention to the management of the land base on Kaho'olawe.

A summary of the major activities impacting natural resource management on Kaho'olawe is presented as Table 1.1. Where possible, the table includes available descriptions of Kaho'olawe's environmental condition at the time of the initiation of the activity.

Table 1.1. Summary of Major Activities Impacting Kaho'olawe's Natural Environment, 900-1989

Year	Activity	Environmental Condition
AD 900-1600	• Low intensity settlement • Primary focus on fishing and coastal settlement	• Native dryland forest • Generally dry but good moisture holding capacity of soils • Springs • Ground water recharge • Minor human impact on the environment
AD 1600-1778	• Intensive use of inland plateau for agriculture and settlement • Population estimates range from 725-1125 • Use of fire for clearing and enhanced grass production	• Dryland forest gradually changing to savanna landscape-grasses, shrubs, low trees • Sandy western edge • Some increase in runoff • Some decrease in evapotranspiration • Land remains productive for local agriculture
AD 1778-1830	• First introduction of western animal species--goats • Population decreases (No clear reason for this)	• Conditions remain the same as above
AD 1830-1859	• Use of island as exile/penal colony during portion of this period • Census figures show 80 people on island • Island designated government lands in the Mahele • First requests for lease and purchase submitted to government • First eyewitness accounts of the island • Cultivation of sweet potatoes, melons, pumpkins and sugarcane reported • Wild pigs and dogs reported	• Savannah still dominant vegetation • First reports of serious goat damage to trees

Table 1.1 continued

Year	Activity	Environmental Condition
AD 1859-1875	• Ranch use begins when government leases issued	• Island considered prime land for grazing • Plentiful grasses
AD 1875-1903	• 12,000-16,000 sheep • 9,000 goats • 900 cattle • First report of large scale erosion • Ranch begins planting to stop soil loss • Kiawe introduced	• Destabilization of slopes and inland soils • Runoff increase • Ground water recharge decrease • Increase of evapotranspiration due to kiawe • Albedo and temperature changes of near surface soils[28]
AD 1903-1910	• Grazing continued • Kiawe trees well established	• Some decrease in evapotranspiration • Reduction in ground water recharge • Large increase in runoff • Widespread reports of blowing red dust over island • Albedo and temperature changes of near surface soils
1910-1918	• Island becomes as forest reserve • Series of technical studies begin • First archaeological survey by J.F. Stokes • Livestock removed • Several thousand goats killed in eradication effort • Reforestation trials conducted with limited success	• Frequent erosion concerns cited in local papers • Some vegetation recovery with goat removal • Destabilization of slopes as goats invade other areas of the island
1918-1920	• Island removed as forest reserve • Lease issued for grazing • Cattle & horses brought in • 800-1000 goats remaining	• Increasing salinity of ground water • Few remaining springs • Runoff increase • Decrease in recharge

Table 1.1 continued

Year	Activity	Environmental Condition
1920-1941	• Grazing and support of small population • Ranch installation of water supply system • Ranch begins eradication of goats and conducts plantings to control erosion • First water resources study confirms deterioration of land to hardpan surface	• Increasing ground water salinization • Siltation of water catchment devices • Flooding • Major goat damage • Runoff increase • Vegetative cover gradually removed from slopes • Increasing gully development in central highlands • Expansion of kiawe forest
1941-1965	• Military use commences, indiscriminate bombing and shelling • Land management activities cease • Population of feral goats increases rapidly • Fires from flares and other military ordnance • Jurisdiction transferred to U.S. Navy in 1953	• Shelling of surface loosens soil, increasing soil erosion by runoff and wind • Increased gully formation, gullies also develop around bomb craters • Runoff increases as a result of fires, vehicular traffic & road construction • Siltation of surrounding waters • Siltation of cisterns • Vegetation denuded by goats and fires • Numerous archaeological sites destroyed and lost
1965-1976	• Protests against military use of Kaho'olawe raised by community and public officials • State conducts revegetation trials	• Island overall in impoverished condition • Planting trials meet with varying success

Table 1.1 continued

Year	Activity	Environmental Condition
1976-1980	• Native Hawaiians begin acts of civil disobedience to protest bombing • Legislative study on Kaho'olawe conducted and resolutions passed to return island to civilian use • Suit filed in federal District Court against military • Navy begins archaeological survey, providing baseline for site conditions, theories of pre-haole environmental destruction developed • State enters Memorandum Of Understanding with Navy for resource management • State conservation plan identified • Navy begins blasting holes for State tree planting, windbreaks planted	• Environmental conditions continue as described since 1953 • Continued runoff increase • Gully development • Siltation
1980-1982	• 'Ohana signs Consent Decree with Navy, begins regular negotiations to review implementation of decree provisions • Bombing limited to one-third of the island • Regular access to 'Ohana granted • Navy conservation plan implemented • Kaho'olawe placed on National Register of Historic Places	• Some increase in runoff • Some decrease in wind erosion • Continued and enhanced gully development • Channel down cutting • Varied success with experimental plantings • Heavy runoff causes increased siltation of near-shore marine waters and destruction of surrounding marine ecology

Table 1.1 continued

Year	Activity	Environmental Condition
1982-1985	• ‘Ohana-Navy negotiations continue • Maui County Community Plan developed • Navy blasts thousands of holes on hardpan surface for tree planting • 5,000 trees planted as windbreaks • Navy begins new goat eradication program • Archaeological data recovery project conducted for important sites threatened by erosion, site conditions evaluated, new interpretation of causes of erosion developed	• Conditions remain the much the same as described above • Detonation of tree holes cause some increase in soil erosion and additional gully development on inland areas
1985	• Native planting project begun	• 16,000 seedlings planted • Goat population reduced • Some decrease in wind erosion • Some increase in gully development
1986	• ‘Ohana lobbies State Legislature for $75,000 to conduct water study of island, funds are appropriated	• Some decrease in runoff as vegetation recovers in non-military zones and goat-cleared areas • Some increase in evapotranspiration
1988-1989	• Initiation and completion of Water Resources Study by Protect Kaho‘olawe ‘Ohana/Fund and U.S. Geological Survey	• Environmental conditions under study

Notes to Chapter 1

[1]The Protect Kaho'olawe Fund is the non-profit corporate arm of the Protect Kaho'olawe 'Ohana.

[2] See reports by J. B. McAllister, "Archaeology of Kaho'olawe," 1933; H. T. Stearns, Geology and Ground-Water Resources of the Islands of Lanai and Kaho'olawe, Hawaii, 1940; Matthew Spriggs, " 'Preceded by Forest': Changing Interpretations of Landscape Change on Kaho'olawe," Appendix I, in P. H. Rosendahl, A. Haun, J. Halbig, M. Kaschko, and M. S. Allen, 1987, Draft Report Kaho'olawe Excavations, 1982-3, Data Recovery Project, Island of Kaho'olawe, Hawaii,1987; R. J. Hommon, National Register of Historic Places Multiple Resource Nomination Form for the Historic Resources of Kaho'olawe, 1980; R. J. Hommon, Kaho'olawe: Final Report of the Archaeological Survey, 1980; R. J. Hommon, Kaho'olawe Archaeological Excavations, 1981, 1983; Carol Silva, Kaho'olawe Cultural Study (Draft) Part 1: Historical Documentation, 1983; P. Rosendahl, A. Haun, J. Halbig, M. Kaschko, and M. S. Allen, Draft Report Kaho'olawe Excavations, 1982-3, Data Recovery Project, Island of Kaho'olawe, Hawaii, 1987; and Inez M. Ashdown, Recollections of Kaho'olawe, 1979.

[3] Matthew Spriggs in his article, " 'Preceded by Forest,' " (1987), charted the sailing routes of early explorers responsible for the first descriptions of Kaho'olawe. He found these accounts were not based on actual visits to the island, but rendered from passing ships sailing along the island's leeward coast. Because of the limited seafaring skills of western voyagers at that time, the preferred sailing routes for ships avoided the unpredictable currents and winds of the Alalakeiki channel to the north of Kaho'olawe and just south of Maui. When ships did venture this route, it appears they kept close to the Maui coast. Thus, little was seen of the inhabited, vegetated windward side of Kaho'olawe. For a summary of the early explorers' accounts of Kaho'olawe see Spriggs, 1987, Table I-1, p. I-11. For studies of Kaho'olawe's inland settlements see R. J. Hommon, 1980a and 1980b; Kaschko, M., "Mapping at Three Inland Settlement Zone Sites" Appendix J, in Rosendahl, P.H., 1987; and Earl Neller, "Settlement Patterns on Kaho'olawe Island, Hawaii," unpublished manuscript, April 1982.

[4] Following the practice of noted historian David E. Stannard, the term pre-haole will be used in place of pre-contact. As Stannard explains: "The conventional phrase describing native societies prior to their contact with the West as 'pre-contact' is both inaccurate and implicitly demeaning to those societies in that it ignores as unimportant inter-cultural contacts that occurred before the arrival of the West. ...in referring to Hawai'i and the Pacific prior to Western contact I will use the more accurate phrase 'pre-haole'---haole being the Hawaiian word for foreigner, with specific reference to Caucasians" (Stannard, 1989:xv).

[5] See Spriggs, " 'Preceded by Forest,' " 1987, p. I-12 to I-37. Matthew Spriggs has done an exceptional review of existing historical and archaeological sources

regarding Kaho'olawe. Spriggs evaluates this information providing a revised interpretation of Kaho'olawe's natural history. His work is quoted extensively throughout this chapter and is important reading for anyone interested in Kaho'olawe's past. For an example of citations of Hommon's pre-haole erosion theory see such authoritative works as Patrick V. Kirch's Feathered Gods and Fishhooks: An Introduction to Hawaiian Archaeology and Prehistory, Honolulu: University of Hawaii Press, pages 153-154.

[6] Small soil particle sizes, limited clay content, and overgrazing which destroyed roots reduced the capacity of the soil to hold together. Near surface moisture was robbed by loss of vegetative cover and by the introduction of kiawe, drying soils and making them more vulnerable to wind erosion. See Spriggs, " 'Preceded by Forest,' " 1987, p. I-44 for a discussion of agricultural sites and crops on Kaho'olawe. In addition to the crops reported by Allen in 1858, other accounts described the cultivation of ti, introduced tobacco and pineapple, as well as dryland taro. The reference for taro cultivation is from Charles N. Forbes, in "Notes on the Flora of Kaho'olawe and Molokini." Forbes' source of information is from a native informant and is contradicted by informant information cited by Hawaiian historian David Malo in Hawaiian Antiquities, 1903. Spriggs indicates that yams and bananas were also grown.

[7] Reports sited in Spriggs, 1987, ' "Preceded By Forest,' " p. I-11 and Silva, 1983 in "Bibliography of News Articles," p.1-4.

[8] Stearns, Geology and Ground-Water Resources of the Islands of Lanai and Kaho'olawe, Hawaii, 1940, p.127. Stearns continued to support his vision for Kaho'olawe's environmental recovery during the Navy's tenure on the island. See H. T. Stearns, "Pre-Navy Kaho'olawe," 1976 and H.T. Stearns, "Kaho'olawe Study 'Snow Job.' " 1977.

[9] Spriggs, " 'Preceded by Forest' " 1987, p. I-12. For a personal account of the eviction of the ranch see Ashdown, Recollections of Kaho'olawe,1979, p. 65-75.

[10] D. E. Foote, E. L. Hill, S. Nakamura, and F. Stephens, Soil Survey of Islands of Kaua'i, Oahu Maui, Molokai, and Lanai, State of Hawaii, 1972; S. D. Warren, E. Vachta, and W. Banwart, "Rehabilitation Proposal for Kaho'olawe Island, Hawaii: An Interim Report," 1988. Soil loss estimates from wind alone are 65 tons/acre/year (Warren et. al., 1988), while water erosion rates from sheet wash alone range between 42 and 527 tons/acre/year.

[11] A family chant provided by Uncle Harry Mitchell of Ke'anae, Maui describes the spring waters of Kamohio on Kaho'olawe in Tom Keene, Kaho'olawe Cultural Study (Draft) Part 2: Ethnography and Cultural Values, 1983, p. 64-65; Ashdown, Recollections of Kaho'olawe, 1979, p. 50 identifies a stone paved well named Waipunapee, "lit. hidden spring water," on the eastern side of Kuhe'eia; see story series in Hawaiian language newspaper, *Ku'oko'a* from February-July 1902 by Kahaulelio, (translated by Mary Kawena Pukui), reprinted in Kaho'olawe Aloha 'Aina, Makahiki 1988-89, p.7 describes the spring at Kanapou by visiting opihi pickers. Interviews with Native Hawaiian residents of arid Makena, Maui (just 8 miles north of Kaho'olawe), reveal brackish water from coastal wells was normally used for drinking by local residents in this arid coastal region before the installation

of modern water transmission lines. Thus, slightly brackish water may have sustained Kaho'olawe's permanent native inhabitants in pre-haole times.

[12] Burt Sakata, Protect Kaho'olawe 'Ohana, Waihe'e, Maui, Hawai'i. Personal communication with A. Mente, July 1989.

[13] Stearns, Geology and Ground-Water Resources of the Islands of Lanai and Kaho'olawe, Hawaii, 1940, p. 129. For a list of the conditional use restrictions the Territory placed upon Angus MacPhee in his Kaho'olawe lease see Appendix A of Hawai'i State Legislature, Kaho'olawe Aloha No: A Legislative Study of the Island of Kaho'olawe, 1977.

[14] The earliest radiocarbon date for occupation is from inland site 398A-1 and calibrates to AD 785-1035. As indicated by the rather large range of settlement dates, "scientific" techniques used for authoritative archaeological conclusions leave much room for interpretation. For pre-haole population estimates for Kaho'olawe see Hommon, 1980a, Appendix A, Figure 3, p.52A and D. E. Stannard, 1989, p. 56.

[15] The first two petitions for Kaho'olawe were submitted in 1847 and 1848 by Z. Kaauwai, the only Hawaiian to petition for the island's use. Both requests were denied. Kaauwai indicated in his petition his wish to become self-sufficient on the land by farming. The subsequent three petitions were submitted by haole primarily interested in ranching. For excerpts from land petitions for Kaho'olawe see Silva, 1983, p. 36-49. Carol Silva did an excellent job compiling a substantial amount of historical references on Kaho'olawe. For those interested in learning about Kaho'olawe's history this document is essential reading.

[16] For an abstract of title for Kaho'olawe see Herbert P. Ewaliko, "Memorandum of Title." Prepared for the Department of Land and Natural Resources, State of Hawai'i, March 9, 1976.

[17] The evidence for the belief that rainfall on Kaho'olawe had decreased due to the loss of forest cover on the island emerged because of the noted decrease in rainfall experienced at Ulupalakua on the Maui coast opposite Kaho'olawe at the turn of the century. The theory was that Kaho'olawe forests in kona weather attracted rain which also fell on Ulupalakua. Destruction of the forests then led to decreased rainfall at Ulupalakua and the demise of the sugarcane operation located there. While the loss of forest cover on Kaho'olawe undoubtedly affected the microclimate and water balance on the island, it is not linked to decreased rainfall on Maui during the period of sugar plantation development. Two variations of this myth (regarding deforestation on Kaho'olawe late in the 19th century) are that kona winds now drop rain on Maui or Lana'i instead of Kaho'olawe. The other blames forest destruction of Haleakala, Maui for causing diminution of the rain on Kaho'olawe.

[18] Stokes seemed particularly impressed with physical remains indicating extensive fishing activity on Kaho'olawe, particularly the abundance and unique features of some of the fishing implements and shrines (see J.F.G. Stokes, excerpts from Field Notes, B.P. Bishop Museum Private Collection, in C. Silva, Kaho'olawe Cultural Study (Draft) Part 1: Historical Documentation, 1983, p. 90-95.

[19] Interesting that fish was not considered a protein substitute for this largely haole dietary preference.

[20] It appears through lease extensions Low remained on Kaho'olawe during much of the forest reserve period to implement the Territory's eradication and planting program. He was ordered off the island by the Territory in 1918 and a new contract for goat eradication is awarded to James C. Crane of Moloka'i (Silva, 1983:104-105).

[21] For Territorial actions regarding Kaho'olawe see Carol Silva, Kaho'olawe Cultural Study (Draft) Part 1: Historical Documentation,1983. For State activities see Hawaii State Legislature, Kaho'olawe Aloha No: A Legislative Study of the Island of Kaho'olawe, 1977. A resolution calling for the Navy to provide an alternative target site to Kaho'olawe and a proposal to provide funds to support negotiations for the return of Kaho'olawe to the State were introduced in 1988.

[22] Observations during the Kaho'olawe Water Study indicate treelines planted parallel to the flow of water exacerbate gully development. A review of aerial photos of the region taken in 1940, 1950, and 1960 indicate the area was not historically dissected with gullies before the trees were planted. The State of Hawai'i contends that the treelines "occasionally lined up with existing gullies." However, it is the position of the researchers of this report that this statement is unsubstantiated. This report recommends that the State evaluate the project based on hydrological factors and the consequent effects of planting parallel to the flow of water.

[23] Field records and observations, Kaho'olawe Water Study. See photos in Chapter 6 of this document. For an update of Navy conservation activities see Pacific Division Naval Facilities Engineering Command, "Conservation Plan for Kaho'olawe, Island, September 1989," prepared for Commander Naval Base, Pearl Harbor.

[24] Site forms for Ahupu, Kaulana and Kuhe'eia bays are particularly revealing because archaeologists identified bomb craters which impacted the integrity of the sites and features in their field drawings. (The site forms mentioned are on file at the State Historic Preservation Division and available for public review.) Also, aerial photographs taken of the Lua Makika area in September 1988 reveals that the surface is pitted with bomb craters. Finally, see reports by then State archaeologist, Earl Neller, which reveal damage of sites by vehicular traffic and ordnance. Neller is also critical of the poor documentation of sites in site forms and the inaccuracy Navy maps, the lack of site markers, and the low level of information provided to military and visiting personnel regarding sites (Earl Neller, "Kaho'olawe Field Trip Report, January 5-8, 1982" and "Erosion of Archaeological Sites on Kaho'olawe, Hawai'i: a Reconnaissance of Selected Sites," September 1981. Reports on File at the State Historic Preservation Division). Neller's criticisms were echoed in a recent Navy internal investigation released in 1988 of a misfiring which sent ordnance into an important archaeological complex, Pu'u Moiwi.

[25] "Conservation Called State's Job-Navy Wins (?) Kaho'olawe Soil War," Honolulu Star-Bulletin, June 23, 1969, p. D-6, c. 1-6.

[26] The acknowledgement that Hawaiians require access to the land for religious use is a tremendous victory for the 'Ohana since part of the Navy's defense during the court case was to prove Hawaiian religion no longer existed. The Navy

has continued to assault the practice of Hawaiian religion and culture through anthropological studies which have characterized the value of aloha 'aina and practice of traditional rituals as "inventions" of modern urban Hawaiians, that do not reflect authentic culture. See Tom Keene, Kaho'olawe Cultural Study (Draft) Part 2: Ethnography and Cultural Values, 1983 whose analysis is derived from anthropologist Jocelyn Linnekin.

[27] The *entire* island was listed on the National Register of Historic Places as a historic district due to the 'Ohana's advocacy despite the Navy's attempt to submit only individual archaeological sites to the Register.

[28] Albedo is the reflectivity of the surface to sunlight normally measured in percentages. The value of albedo is changed when the surface conditions change (i.e. from vegetation to bare soil). Albedo of bare soil is 25-40%, whereas dry savannah albedos are 10-20%. Reflection of solar radiation back to the atmosphere means leass is available to the soil and plants for energy-driven processes. High albedos are associated with deserts and are indicators of environmental stress (i.e. desertification).

Chapter 2

Purpose and Design of the Kaho'olawe Water Study

Introduction

The Kaho'olawe water study takes a comprehensive and island-wide approach toward the examination of both surface and ground water resources, their collective potential, and the requirements for island-wide resource management. It is the intent of this study to provide a basis for future water resources research and development activity on Kaho'olawe as well as to provide a framework for the comprehensive management of Kaho'olawe's water and land environment.

Effective management of the water resource on Kaho'olawe is key to the revegetation of the island and stabilization of Kaho'olawe's soil and archaeological resources. Moreover, by arresting soil erosion, the existing non-point source pollution of surrounding coastal waters would be substantially reduced or eliminated.

Purpose

The objectives of the project are to:

1. Identify and investigate all potential sources of water on Kaho'olawe and develop projects which demonstrate both the use and control of water;

2. Install monitoring systems which will provide hydrologic data on surface and ground water characteristics;

3. Identify water resource requirements, formulate a plan and develop cost estimates for the development of all viable water resources;

4. Prepare a report to document the planning criteria, evaluations, research and recommendations which were made in formulating the project and results.

Approach and Methodology

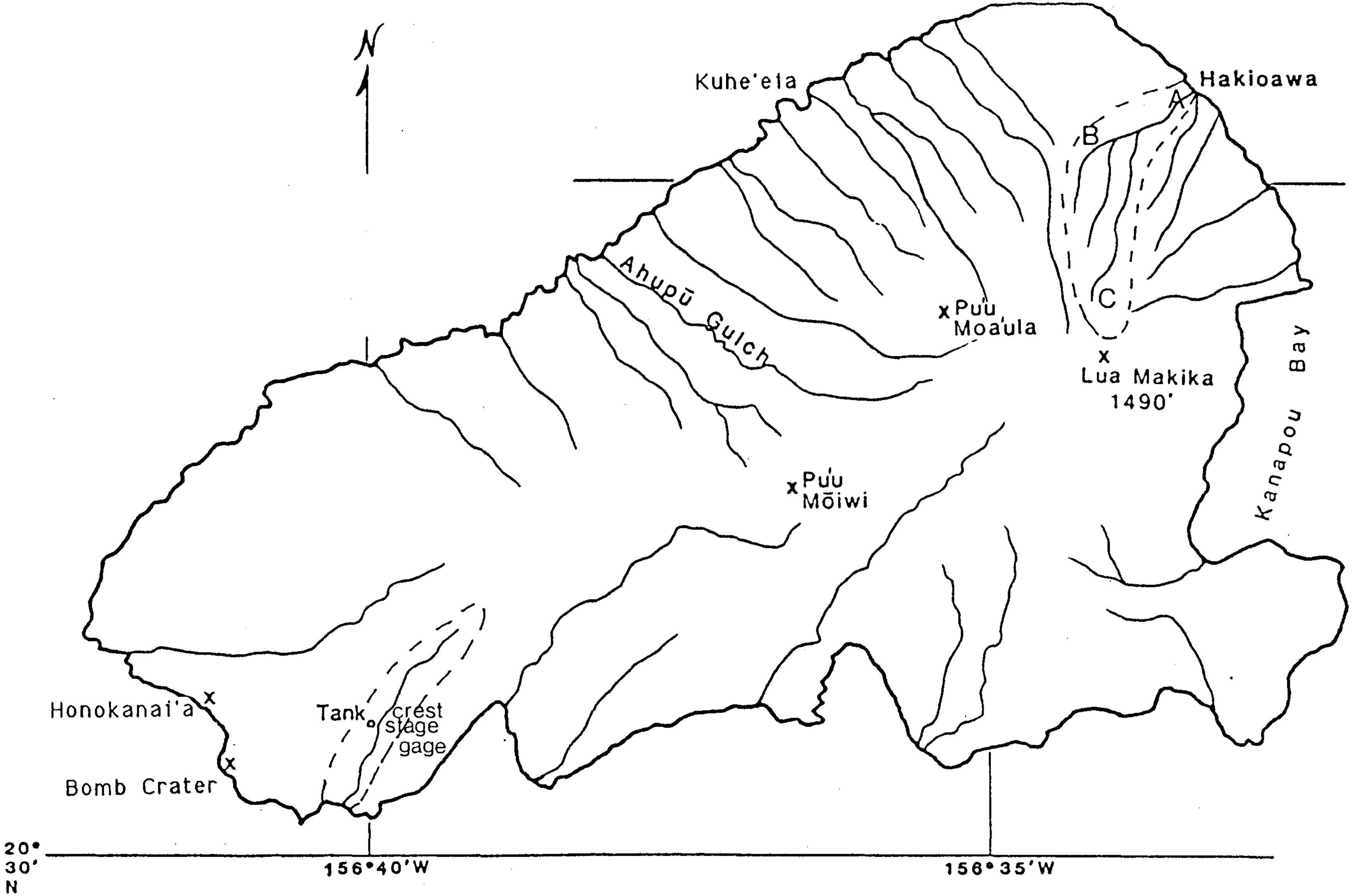
The investigation of the sources and occurrence of surface and ground water on Kaho'olawe takes an island-wide approach and is rooted in the foundations of hydrologic and watershed management science. It is necessary to review this perspective as it provides the framework for investigation as well as for water resources management on Kaho'olawe.

First, the elements of the hydrologic cycle on Kaho'olawe--evaporation, rainfall, runoff, infiltration and ground water storage--and the understanding of the nature and fluctuation of these elements over time, is key to development planning on Kaho'olawe. The hydrologic cycle for Kaho'olawe must be identified as it relates to the overall supply, distribution and storage of water on Kaho'olawe. With a knowledge of the characteristics of the cycle on Kaho'olawe, it is possible to determine, for example, the quantity of water generated per rainfall event, and its potential for harvesting. The hydrologic cycle and its characteristics also provide guidelines for the reclamation of hardpan soils so that infiltration can be increased to capture and hold moisture rather than shed water as runoff. The hydrologic cycle is incorporated into this study on an island-wide basis by considering the ***water balance*** over the entire island.

Secondly, Kaho'olawe, from a water resources perspective, consists of numerous watersheds, or regional topographical divides, dissected by small tributaries which drain water to a single stream. A water balance calculation can be obtained for a single large or several small watersheds. Within a watershed, land use activities impact the distribution and character of water by altering some portion of the hydrologic cycle. Analysis of the water balance and land uses within a watershed, in addition to the analysis of the differences in overall watershed characteristics, provides the basis for the location and development of favorable water supplies. Moreover, the impacts of resource management strategies can be more readily assessed and effective if undertaken from a watershed analysis.

Guided by this perspective, the study developed demonstration projects and instrumentation efforts in selected watersheds of Kaho'olawe. Figure 2.1 illustrates the project study areas. Thus the integration of hydrology with the watershed approach on an island-wide basis provides a convenient planning tool as well as a series of logical geographic planning units for the investigation of water resource development and management on Kaho'olawe.

Finally, no study of the water resources of Kaho'olawe could ignore the important impact of land use on water supply, quality and runoff characteristics. It is clear from historical records and soil types on Kaho'olawe, for example, that the island had a different water environment in the past, and that intensive grazing in the last century removed vegetation, trampled soils and initiated massive soil erosion and instability. This was followed by the cessation of all land management activity, coupled with military land use which may have added to further environmental deterioration.



Scale: 1 inch = 1.4 miles

Figure 2.1. Map of Kaho'olawe showing the location of Kaho'olawe Water Study project areas. The research watersheds are outlined by dotted lines. Site "A" designates the location of the stream gage, rain gage and water level recorder in Hakioawa Gulch. Site "B" designates the location of soil and water conservation structures at the Mauka I area. Site C designates the general location of soil and water conservation structures at the Mauka II (hardpan) area. Hydrologic analysis was conducted over the entire island. [Note: the southwest crest stage gage is scheduled for installation.]

Presently, runoff from an important archaeological area, the hardpan, moves as overland or sheet flow over the surface, washing archaeological sites and foundation soils downslope. Moreover, as more soil is lost, the medium for vegetation regrowth is diminished. Hence, the capture of soil is key to the retention of moisture as well as to the control of water as it moves downslope, and land use management must be seen as integral to the management of water on Kaho'olawe.

Drawing upon this comprehensive background and framework, the project combines both standard engineering tools and hydrologic analytical techniques and applies them to the implementation of a number of study tasks identified in the contract scope of work.

Chapter 3

Description of the Physiology & Resources of Kaho'olawe

Physiography

The island of Kaho'olawe lies in the rain shadow of the dormant volcano Haleakala, and is 6.75 miles southwest of Maui and 92 miles southeast of Honolulu. A small island, Kaho'olawe is 6 miles wide, 11 miles long and has an approximate area of 45 square miles or 28,800 acres. Elevations on Kaho'olawe range from sea level to 1,477 feet (450 meters), and in profile the island has the shape of a broad, smooth dome (Figure 3.1).

Kaho'olawe is an extinct shield-shaped volcano composed of thin lava flows poured in rapid succession from three major rift zones (Figure 3.2). There is one major volcanic vent, Lua Makika, with smaller cinder cones also present (Lua Kealialuna, Pu'u Moiwi, Moa'ula, Pu'u Kolekole and Lua Kealialalo). A considerable portion of the eastern and southeastern coasts of Kaho'olawe consist of high sea cliffs and hanging valleys, while the northern, northwestern and southwestern coasts have gentle slopes and small, crescent-shaped white sand beaches.

Major drainages on the island radiate from Lua Makika, with the smaller cinder cones impacting the development of streams and drainage networks. There are 63 major watersheds on Kaho'olawe.

The slopes of Kaho'olawe are corrugated with numerous gullies ranging from 20 to over 150 feet in depth. Over one-third of the island has been eroded down to a barren hardpan surface consisting of partially decomposed basalt which is in many cases impervious to rainfall.

Climate

The location of Kaho'olawe with respect to the major water-bearing winds and local topographic influences places the island within a semi-arid climatic zone, with an average annual rainfall ranging from 18--27 inches.[1] The volcano Haleakala, on Maui, deflects northeast tradewinds, and through orographic influence, removes a considerable amount of moisture from these winds before they reach Kaho'olawe. However, Kaho'olawe remains quite windy; the "dust bowl," as referred to by Stearns. The pruned-shape of trees also testify to the work of the wind in shaping Kaho'olawe. Winds primarily arise from the east.

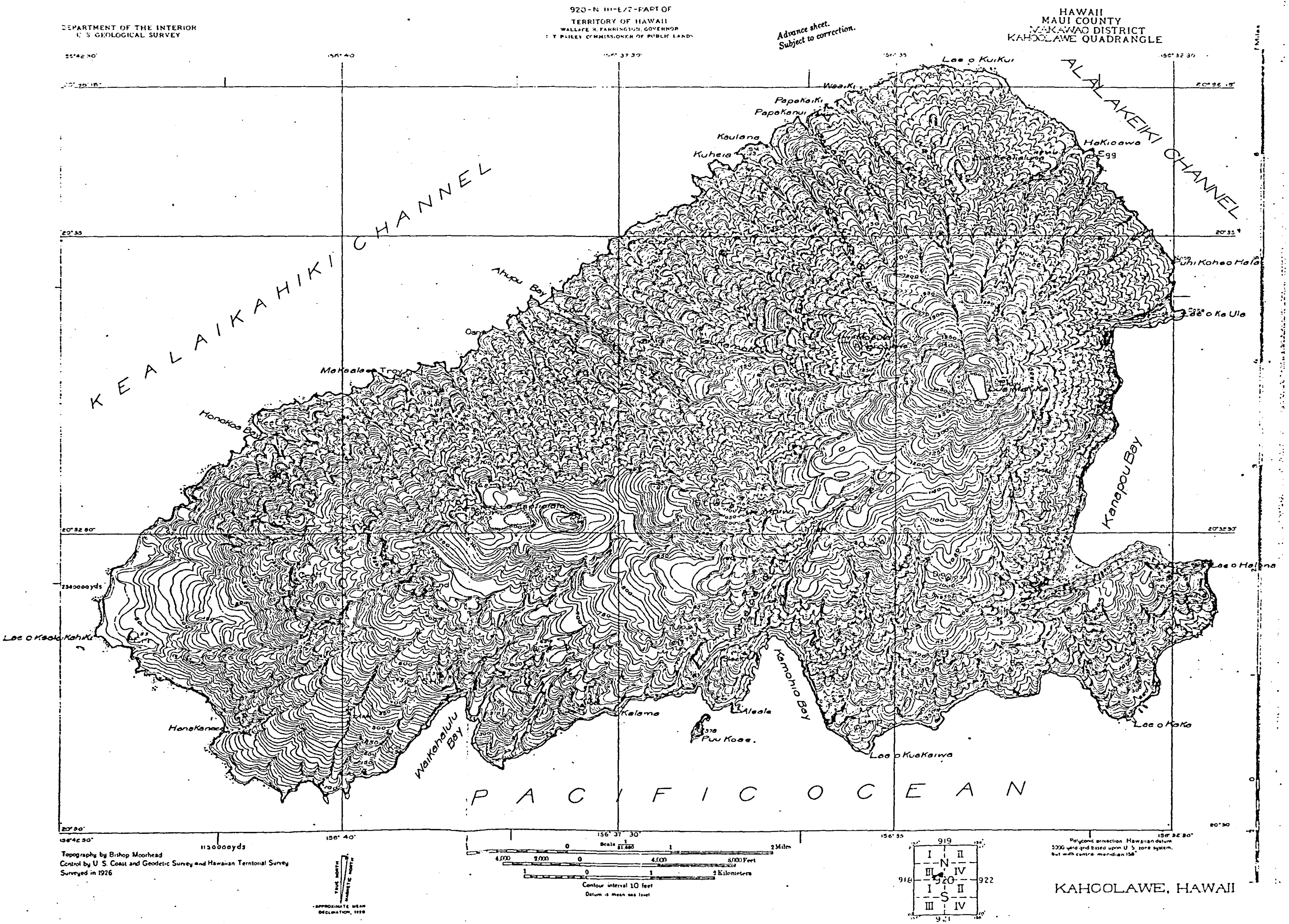


Figure 3.1. Map of Kaho'olawe showing major topographical features (after U.S.G.S., 1981).

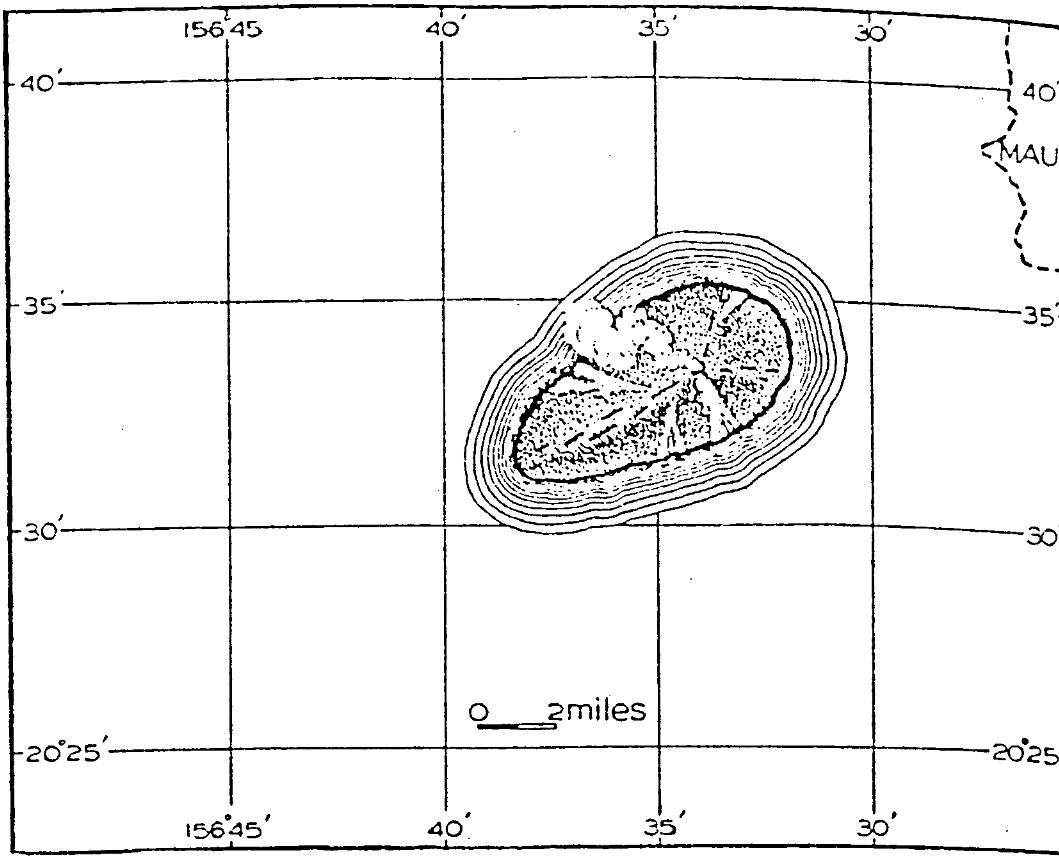


Figure 3.2. Map of Kaho'olawe showing major rift zones identified by Stearns (1940). The 3 rift zones are similar in orientation to the rift zones located around Haleakala, Maui.

Kona storms bring widespread rainfall to Kaho'olawe, and a single high intensity Kona storm may bring as much as 7 or 8 inches of rain over a 24 hour period. Three such storms occurred during the course of this project, totaling more than 15 inches of rainfall.[2]

Fog and cool, damp mist also prevail on Kaho'olawe's summit at Lua Makika. This occurs frequently in the winter, with dew also present on early summer mornings.[3] Research on fog and its contribution to the overall water balance of Mauna Loa on the island of Hawai'i suggests that the volume of fog drip may amount to as much as 60% of total precipitation (Juvick and Ekern, 1978).

Existing rainfall information was obtained from records of the rainfall gage station installed on Kaho'olawe as a part of the project (Table 3.1). As reported in Tables 3.2 and 3.3, historical precipitation data are sparse; there are only three years in the entire record in which rainfall was measured for 12 months of the year. At present, there are two functioning rain gages on Kaho'olawe; one station is located at Hakioawa and was installed in 1988 as a part of this project. The other was installed the following year at Moa'ula near the island's summit by the U.S. Navy as part of a larger weather station.[4] Inspection of other gages on the island that are maintained by the Navy revealed that numerous stations were in disrepair, with some gages completely blown over. One station was blown over in a storm in November 1988 and remained inoperable when last checked in March, 1989.

Despite the paucity of data, however, it is possible to discern from indirect evidence that the northern side of Kaho'olawe receives greater rainfall than the southern side. For example, the size and number of drainages on the northern side of Kaho'olawe are greater than on the southern side; indirect flow calculations in gulches on either side of the island support these assertions.[5] Clearly, there is more dissection of the northern slope than the southern slope. The clay mineralogy of soils on either side of the island, discussed in a later section of this report, also supports the contention that a greater quantity of water falls on the northern side of Kaho'olawe. More moisture is necessary to produce the specific clay assemblages present on the northern side of Kaho'olawe.[6]

The distribution and occurrence of rainfall and moisture on Kaho'olawe also permits the development of microclimatic zones, in which certain kinds of vegetation thrive. This is especially apparent on the northeastern side of Kaho'olawe, where several niches permit the growth of selective plant species. For example, field investigations during this study indicated that saltbush (*Atriplex senibaccata*) and other species in general had greener, fuller leaves and looked far healthier in a particularly barren area of the northeastern hardpan than at lower elevations in presumably thicker soils. A likely key factor leading to this observation is moisture brought in through fog and occasional mist.

The distribution of rainfall on Kaho'olawe, and the subsequent development of microclimatic zones, also influences the kind and nature of soil development. This has implications for erosion potential, drainage, and infiltration properties which affect resource management planning.

Table 3.1.
Regional Rainfall Records for Lana'i Maui, and Kaho'olawe for Various Years

STATION LOCATION	ELEVATION (in feet)	DATES	RAINFALL PER MONTH (in inches)												TOTAL AVE.
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Hakioawa Gulch (Kaho'olawe)	8	Oct 1988	---	---	---	---	---	---	---	---	---	7.60	5.00	7.26	19.86
Makena Golf Course (Maui)	87	1987-88	2.73	1.09	0.02	0.36	0.29	0.48	0.90	0.28	0.20	5.25	4.66	4.50	19.77
Kihei (Maui)	85	1935-83	2.10	1.50	1.30	0.30	0.10	0.00	0.00	0.00	0.00	0.30	0.50	1.40	12.80
Ulupalakua Ranch (Maui)	1,900	1905-83	3.10	2.60	2.40	2.20	1.60	1.30	1.50	1.40	2.20	1.50	1.30	2.60	31.00
Lana'i City (Lana'i)	1,620	1930-83	4.80	2.40	3.20	1.90	1.90	0.90	1.40	1.60	1.40	2.10	2.00	3.30	33.40
Kaumalapau Harbor (Lana'i)	30	1948-83	2.90	1.60	1.10	0.40	0.90	0.20	0.20	0.40	0.40	0.90	0.60	2.00	14.70

Source: Division of Water and Land Development, Department of Land and Natural Resources.

Table 3.2. Rainfall Data for Inactive Rain Gages [1904 to 1917], Island of Kaho'olawe

STATION	YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	TOTAL (inches)	Mons Oper
		RAINFALL PER MONTH (in inches)													
Kuhe'eia	1904	Readings begin October 8									2.32	2.40	1.47	6.19	3
	1905	0.43	0.77	0.34	2.51	0.53	1.00	1.54	2.34	0.40	–	–	–	9.86	9
	1911	Readings begin September 25								0.44	0.32	0	0	0.76	3+
	1912	No monthly data												7.44	12
	1913	" " "												16.60	12
	1914	" " "												12.17	12
	1915	" " "												8.20	9
	1917	1.72	1.99	1.62	0.15	3.71	0	0	0	0	0	2.25		11.44	12
Lua Kealialuna	1911	Data for September 25-30, Oct 1-7								0.69	0.36	0	0	1.05	2+
	1912	No monthly data												8.23	12
	1913	" " "												16.42	12
	1914	" " "												13.31	12
	1915	" " "												7.35	9
	1917	1.97	1.92	2.01	0.25	4.51	0	0	0	0	0	2.94		13.60	12
Lua Kealialalo	1911											0	0	0	2
	1912	No monthly data												5.33	12
	1913	" " "												11.80	12
	1914	" " "												9.93	12
	1915	" " "												5.68	9
	1917			0.88	0	1.10	0	0	0	0	0	1.92		7.60	12
Moa'ula	1911	Begin September 25								1.13	0.37	0	0	1.50	3+
	1912	No monthly data												10.24	12
	1913	" " "												18.34	12
	1914	" " "												12.39	12
	1915	" " "												9.64	9
	1917	1.92	6.00	2.36	0.05	4.25	0	0	0	0	0	6.20		20.78	12

Source: Division of Water and Land Development, Department of Land and Natural Resources, State of Hawai'i. Observer 1911-17, Mr. Eben Low, lessee.

Table 3.3. Summary of Rainfall Data from Active Rain Gage near Lua Makika, Kaho'olawe Island, 1971 - 1977

Date of Reading	Rainfall (in inches)	Estimated Annual Totals (in inches)
1-11-71	Gage installed	
5-14-71	9.20	
7-13-71	1.80	
11-3-71	1.98	1971:18
3-28-72	8.00	
6-20-72	3.32	
7-31-72	0.87	
11-4-72	2.54	1972:14
2-16-73	3.70	1973:11
3-27-74	No reading	
11-30-74	3.68	1974:25
2-28-75	4.56	1975:12
2-28-76	2.64	
8-31-76	2.00	1976:12
6-30-77	4.08	

Source: On file, Division of Water and Land Development, Department of Land and Natural Resources, State of Hawai'i quoted in Ewart, 1978, p.25.
Note: Only one reading was made between 1975 and February 1976, February 1976 and August 1976, and August 1976 and June 1977.

Reported temperatures on Kaho'olawe range from a low of 74°F to a high of 95°F, however, fieldtrips to the island indicate temperatures during the day and night can drop much lower. Very limited wind or humidity data are available for Kaho'olawe. Table 3.4 presents the only available humidity data.

Because water resources are sparse on Kaho'olawe, it is necessary to consider even meager amounts of water as valuable tools in a revegetation strategy; clearly, the concept of climatic variation is important to devising resource management strategies for Kaho'olawe. Of interest is the fact that the State of Hawai'i, private researchers, the U.S. Soil Conservation Service (1979), and the University of Hawai'i Water Resources Research Center and Agricultural Extension Services all have developed lists of plant species suited to certain climatic zones on other islands in Hawai'i. Many of the species are known to thrive on fog and mist. These lists, and other species particularly adapted to Kaho'olawe, are applied to the development of resource management strategies for

Kaho'olawe in subsequent chapters of this report.

Table 3.4. Humidity Data for Kaho'olawe, June 1970
[Readings taken between 6:00 a.m. and 2:45 p.m.]

Date	Location	Elevation	Humidity	Time
June 6, 1970	Navy Camp	10 ft	68%	6:00 a.m
a.m.	Plot #3	1,430 ft	63%	10:00 a.m.
p.m.	Plot #4	1,220 ft	52%	1:00 p.m.
	Plot # 5	830 ft	57%	2:45 p.m.
June 7, 1970	Navy Camp	10 ft	73%	6:00 a.m.
a.m.	Plot #1	600 ft	61%	11:00 a.m.
p.m.	Plot #6	440 ft	61%	12:30 p.m.
	Plot #2	10 ft	46%	2:00 p.m.

Source: Division of Land and Water Development, Department of Land and Natural Resources, Office Files, 1970. Humidity readings taken by DLNR staff using a psychrometer. Temperature during this period ranged from 74°F - 98°F. Wind direction as observed at the Navy camp ranged from 70°E of North to 10°S of East.

Vegetation

As mentioned earlier, archaeobotanical information reveals the presence of mixed dryland forest prior to European contact on Kaho'olawe. With settlement of the inland plateau and development of agriculture, a savannah type vegetation dominated by native grasses, shrubs and small trees prevailed on Kaho'olawe. Chapter 1 sites the early descriptions of the island's vegetation in the 1850's.

Noted botanist Harold St. John reviews the findings of the major botanical studies of Kaho'olawe.

> Jules Remy was in the Hawaiian Islands from 1851 to 1855, and once during that period he visited Kaho'olawe. This was just at the end of the penal colony period, and probably the natural vegetation was little disturbed. He collected twelve plant species on it, including the native shrubs *Santalum elliptcum* [*'iliahi alo'e*], *Hibiscus brackenridgei [ma'o hau hele*], and the two endemic species of *Gouania* [*Gouania remyi and Gouania cucullata*]. The *Santalum* might have grown all over, from the shore to the volcanic crests, and a single bush of it was later found at the

southwest end of the island by Stearns (1940:124). The *Hibiscus* probably grew in rocky gulches in the upland. It is a stout shrub or small tree, and may have added to the forest cover.

...Early accounts of the island describe it as forested on top. Of this tree growth only *Erythrina sandwicensis* [wiliwili] persisted, and specimens of it were collected by Forbes in 1913 from one of the few surviving individual trees... He learned from previous visitors that they had also seen on the island the tree *Reynoldsia sandwicensis* [*'ohe]*, and the shrubs *Dodonaea sandwicensis* [*a'ali'ii*] *Styphelia tameiameiae* [*pukiawe*], *Myoporum sandwicense* [*naio*], and *Euphorbia multiformis* [*'akoko*].

Another shrub, *Neraudia kahoolawensis*, described by Hillebrand in 1888, had become extinct by 1913. Among these species, the only real trees are the *Erythrina* and the *Reynoldsia*, both of which will grow to good size, even in arid places, but there they occur as scattered individuals and can scarcely be said to produce much of a forest. At least it is of a wide open savannah type.

The other known native plants which are shrubs would have made some thickets between the trees, and filling in would be the common "pili" grass, *Heteropogon contortus*. These shrubs were the *Neraudia, Dodonaea, Styphelia, Myoporum*, and *Euphorbia*, and to these we now add *Gouania Remyi* and *G. cucullata*. Several other shrubs in the vegetation of the littoral zone are here omitted because they would not have formed part of the upland savannah forest vegetation.

There was one other endemic species collected by Remy, *Lipochaeta kahoolawensis* Sherff, and an indigenous one, *L. connata* (Gaud.) DC. These are doubtless gone, but another endemic one was collected by Bryan in 1931, *L. Bryannii* Sherff. Together, then, the known endemics of the now desolated island Kaho'olawe are five: *Gouania cucullata, G. Remyi, Neraudia kahoolawensis, Lipochaeta bryanii*, and *L. kahoolawensis*. (St. John, 1969).

Overgrazing and the concomitant loss of soil in the late 19th century encouraged ranchers to introduce many exotic plant species to Kaho'olawe which had an important effect on the vegetation pattern of the island.

In 1913, Charles N. Forbes, botanist on the Bishop Museum expedition to Kaho'olawe, collected 16 native and 15 introduced species on the island. Tree tobacco (*Nicotiana glauca*) was the most common shrub on the island, growing on the rocky slopes and the sides of craters. Pili grass (*Heteropogon contortus*) covered the southern and eastern slopes, and small groves of kiawe (*Prosopis pallida*) were found at the mouths of the island's gulches (EIS Corp., 1982:2-45).

In 1917, the period Kaho'olawe was designated forest reserve, Charles S. Judd, then Territorial Forestry Superintendent, reported white cactus growing in a few areas on the north side of the island and that ironwoods (*Casuarina*) had been planted on the top of the island. Several exotic grasses had been introduced. He reported about one-third of the island was covered with kiawe which had spread up the ridges to as high as the 1,200 foot elevation. However, stands of tall pili grass still dominated the northeast side of the island in long, gentle slopes. Judd found the southeast side of the island to be barren and rocky.

In 1918, Kaho'olawe was leased out to Angus MacPhee who removed 13,000 goats from the island in 3 years. A fence was constructed across the island to keep the remaining goats and sheep to the gullies and steep hillsides on the eastern end of the island. MacPhee began a vigorous revegetation program planting 5,000 trees, dispersing hundreds of pounds of Australian saltbush seeds and a number of grasses. In 1931, when E. H. Bryan surveyed the island he reported 11 native species including the endemic *Lipochaeta bryanii* and 30 introduced species. *Kiawe* and klu (*Acacia farnesiana*) were the dominant trees present, in addition to salt bush, cocklebur (*Santhium saccharatum*), and *pua kala* (*Argemone glauca*).

At the time of Stearns' 1939 reconnaissance of Kaho'olawe, only a few native trees had survived the voracious goat population, ranch livestock, and aggressive *kiawe* trees. Stearns reported 80 *wiliwili* trees, a single sandalwood bush, and one lone ti plant (*Cordyline terminalis*). Among the exotic species identified, Stearns lists guava (*Psidium guajava*), ironwoods, eucalyptus, sisal (*Agave sisalana*), cactus (*Opuntia magacantha* and *Nopalea cochenillifera*), haole-koa (*Leucaena leucocephala*) and the predominant *kiawe* and tree tobacco.

A botanical survey was conducted in 1978 as a part of the preparation of the Environmental Impact Statement for the U.S. Navy's military training complex (EIS Corp, 1979). Five major vegetation zones were identified on the island. The zones include: 1) hardpan desert vegetation (dominated by saltbush, tree tobacco and *kiawe*), 2) *kiawe* scrub forest, 3) grasslands, 4) coastal strand vegetation and 5) cliff vegetation. A map showing these zones is presented as Figure 3.3. Very few native grass and shrub species remain on Kaho'olawe. Exotic trees and grasses introduced to the island beginning in the late 19th century competed for moisture supply, limiting the ability of native species to survive the onslaught of goats and subsequent soil erosion.

In 1982-83 an archaeobotanical analysis was conducted on the remains from a few of Kaho'olawe's firepits. Additional native plant species were identified during the study. Table 3.5 provides a comprehensive list of native plant species reported on Kaho'olawe to date.

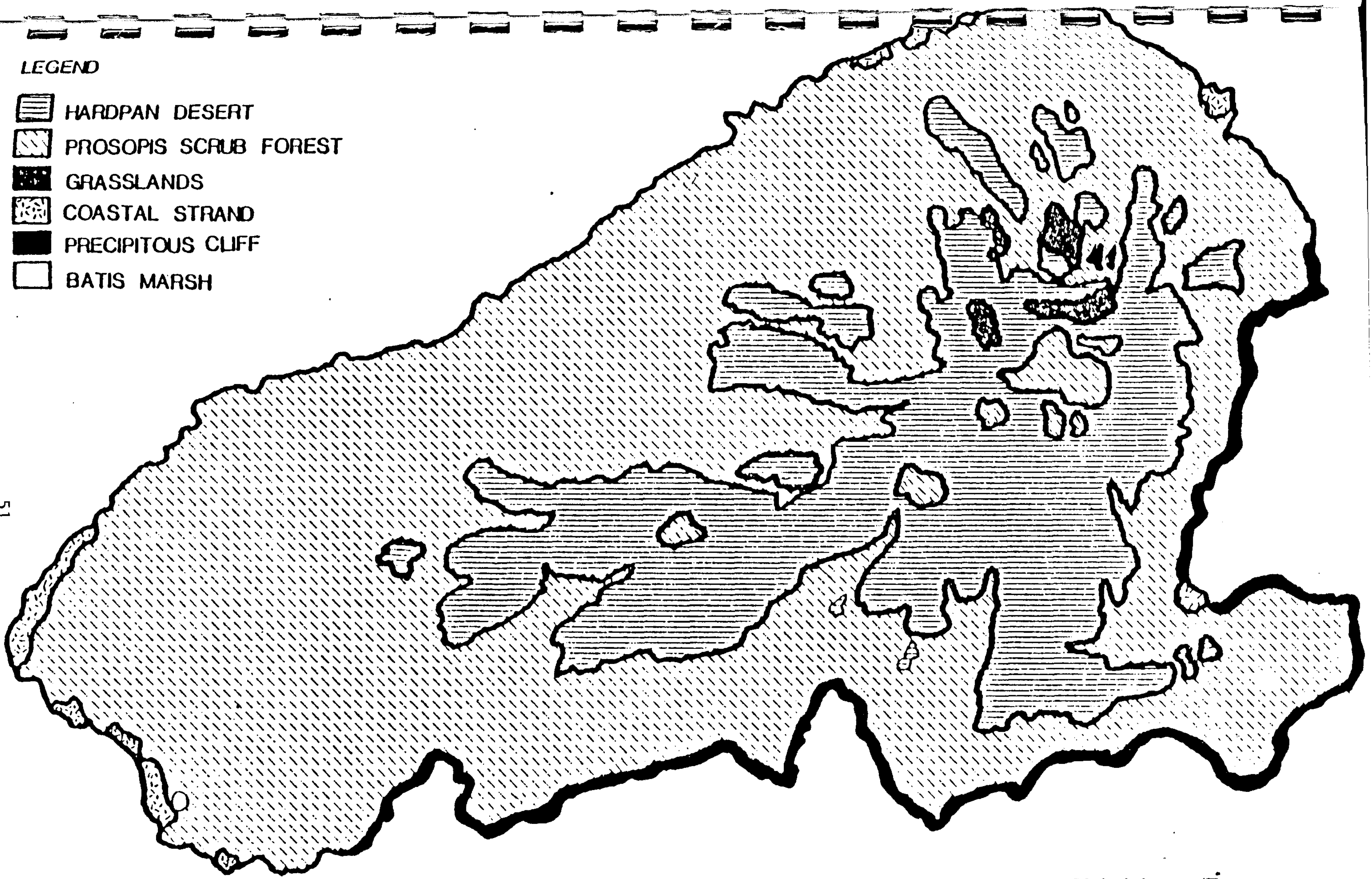


Figure 3.3. Map showing location of major vegetation zones on Kaho'olawe (From Environmental Impact Study Corporation, 1979).

Table 3.5. Comprehensive List of Native Plants Known from Kaho'olawe [7]

Scientific Name	Hawaiian/Common Name	Status[1]
1. PTERIDOPHYTA		
Adiantaceae		
Doryopteris decipens (Hook.) J. Sm.	'iwa'iwa	E
Doryopteria decora Brack.	'iwa'iwa	E
Davalliaceae		
Nephrolepis sp.	---	I
Thelypteridaceae		
Christella dentata (Forssk.) Brownsey & Jermy	---	I(?)
2. ANGIOSPERMAE MONOCOTYLEDONAE		
Cyperaceae		
Elaeocharis sp.	---	?
Dioscoreaceae		
Dioscorea alata L.	uhi / yam	P
Graminae		
Eragostis variabilis (Gaud.) Hbd.	‘emoloa, kalamalo	E
Eragrostis sp.	---	?
Heteropogon contortus (L.) Beaw.	pili	I
Panicum cornae St. John sp. nov.	---	E
Panicum fauriei Hitchc.		E
Panicum nubigenum Kunth	---	E
Panicum nubigenum Kunth var. *latius* St. John var. nov.	---	E
Panicum torridum Gaud.	kakonakona	E
Panicum spp.	---	?
Saccharum officinarum L.	ko / sugar cane	P
Sporobolus virginicus (L.) Kunth	‘aki‘aki	I

Source: M.S. Allen, 1987, p. A-31 to A-35. Allen used three botanical studies to compile this list: the Environmental Impact Statement for the Kaho'olawe Training Area (EISC 1979: Appendix E;) and palaeo-ethnobotanical studies by M. S. Allen 1983 and Gail Murakami 1983.

[1] Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction.

Table 3.5. (Cont.)

Scientific Name	Hawaiian/Common Name	Status[1]
Liliaceae		
Cordyline terminalus (L.) Kunth	ki, ti	P
Musaceae		
Musa sp.	mai'a; banana	P
Palmae		
Cocos nucifera L.	niu; coconut	P
Pandanaceae		
Pandanus odoratissimus L.	hala	I,E
3. DICOTYLEDONAE		
Aizoaceae		
Sesuvium portulacastrum (L.) L.	‘akulikuli	I
Amaranthaceae		
**Nototrichium* sp.	kulu'i	E
Araliaceae		
Reynoldsia sandwicensis Gray [or *R. mauiensis* Sherff]	‘ohe	E
Boraginaceae		
Heliotropium anomalum H. & A var. *argenteum*	hinahina-kakahakai	I
Heliotropium curassavicum L.	nena, kipukai	I
Capparidaceae		
Capparis sandwichiana DC. var. *zoharyi* Deg. & Deg.	puapilo, maiapilo	E
Chenopodiaceae		
Chenopodium cf. *oahuense*	‘aweoweo, aheahea	E
Compositae		
Bidens mauiensis (Gray) Sherff	--	E

* Taxa known from archaeological materials.
[1]Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction.

Table 3.5. (Cont.)

Scientific Name	Hawaiian/Common Name	Status[1]
Compositae (Cont.)		
Gnaphalium sp.	--	?
Lipochaeta bryanii Sherff	nehe	E
Lipochaeta connata (Gaud.) D.C.	nehe	E
Lipochaeta kahoolawensis Sherff.	nehe	E
Lipochaeta lavarum (Gaud) DC. var *ovata* Sherff	nehe	E
Lipochaeta aff. *rockii* Sherff	nehe	E
Lipochaeta sp.	nehe	E
Convolvulaceae		
Cressa insularis House	native cressa	I
Ipomoea batatas (L.) Poir.	ʻuala (sweet potato)	P
Ipomoea brasiliensis (L.) Sweet	pohuehue	I
Ipomoea cairica (L.) Sweet	koali	I
Ipomoea congesta	koali-ʻawania	I
Ipomoea tuboides Deg. & van Ooststr.	---	E
Jacquemontia sandwicensis Gray var. *sandwicensis*	pa'u-o-Hi'iaka	E
Jacquemontia sandwicensis Gray var. *tomentosa* (Choisy) Hbd.	pa'u-o-Hi'iaka	E
**Merremia aegyptica* (L.) Urban	---	I(?)/P(?)
Cruciferae		
Lepidium o-waihiense C. & S.	ʻanaunau	E
Cucurbitaceae		
**Lagenaria siceraria* (Molina) Standl	ipu	P
**Sicyos* sp.	'anunu	E
Epacridaceae		
Styphelia tameiameiae (Cham.) F. Muell.	pukiawe	I

* Taxa known from archaeological materials.
\# Previously considered to be post-contact introductions, these taxa have since been discovered among the 1778 botanical collections of Nelson (St. John 1978)
[1]Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction.

Table 3.5. (Cont.)

Scientific Name	Hawaiian/Common Name	Status[1]
Euphorbiaceae		
**Aleurites moluccana* (L.) Willd.	kukui	P
Euphorbia celastroides var. *kohalana* Sherff	'akoko	E
Euphorbia celastroides Boiss. waikoluensis Sherff	'akoko	E
Euphorbia multiformis H. & A. var. *microphylla* Boiss.	'akoko	E
Euphorbia glomerifera (Millsp.) L.C. Wheeler	'akoko	E
Goodeniaceae		
Scaevola taccada (Gaertn.) Roxb.	naupaka-kahakai	I
Leguminosae		
Erthyrina sandwicensis Deg.	wiliwili	E
Sesbania tomentosa H. & A.	'ohai	E
Tephrosia purpurea (L.) Pers.	'auhuhu	P
Malvaceae		
Abutilon incanum (Link) Sweet	ma'o	I
Gossypium sandvicense Parl.	ma'o	E
Hibiscus brackenridgei Gray	ma'o-hau hele	E
Sida fallax Walp.	'ilima	I
Myoporaceae		
Myoporum sandwicense Gray	naio	E
Nyctaginaceae		
Boerhavia diffusa L.	alena	I
Oxalidaceae		
#*Oxalis corniculata* L.	'ihi	I(?)/P(?)
Papaveraceae		
Argemone glauca Pope	pua-kala	E
Argemone glauca var. *inermis* Deg. & Deg.	pua-kala	E

* Taxa known from archaeological materials.

\# Previously considered to be post-contact introductions, these taxa have since been discovered among the 1778 botanical collections of Nelson (St. John 1978)

[1]Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction.

Table 3.5. (Cont.)

Scientific Name	Hawaiian/Common Name	Status[1]
Portulacaceae		
Portulaca lutea Soland. ex Forst. f.	'ihi	I
Portulaca sclerocarpa Gray	'ihi-makole	E
Rhamnaceae		
Gouania cucullata St. John	-	E
G. remyi St. John	-	E
Rubiaceae		
**Canthium* sp.	-	I
Santalaceae		
Santalum ellipticum Gaud.	‘iliahi	E
Sapindaceae		
Dodonaea sandwicensis Sherff	a‘ali‘i	I
Solanaceae		
Lycium sandwicense Gray	‘ohelo-kai, ‘akulikuli-‘ohelo	I
**Nothocestrum* sp.		
Solanum nigrum L.	popolo	I(?)/P(?)
Sterculiaceae		
Waltheria americana L.	hi‘aloa, ‘uhaloa	I
Urticaceae		
Neraudia kahoolawensis Hbd.	---	E
Zygophyllaceae		
Tribulus cistoides L.	nohu	I

* Taxa known from archaeological materials.
\# Previously considered to be post-contact introductions, these taxa have since been discovered among the 1778 botanical collections of Nelson (St. John 1978)
[1]Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction.

Geology

Introduction

The geology of Kaho'olawe is an important determinant of the supply, occurrence and quality of water on the island. Hence, an understanding of Kaho'olawe's origin, the type of rock materials present and their weathering products, and rock structural and textural features is essential to water resource management planning.

The first comprehensive study of the geology of Kaho'olawe was conducted by Stearns (1939), who also conducted the first water resources survey, and MacDonald (1940), who analyzed the petrography of selected rocks from Kaho'olawe. Since that time, there have been significant advancements in the science of geology, in the knowledge of the origin and formation of the Hawaiian islands, and in the application of a range of tools to the understanding of water resource occurrence in volcanic terrains. Unfortunately, few of those tools have been applied to Kaho'olawe, with the result that there is still much-needed geologic research on the island.

Recently, however, research regarding the origin and chemical composition of Kaho'olawe's rocks sheds new light on the origin and composition of Kaho'olawe (Fodor, Bauer, Jacobs and Bornhorst, 1987 and Clague, 1988). This section will provide an update of the geology of Kaho'olawe in light of recent research, field work conducted during the course of the project, and existing material. A later section of this report on the hydrogeologic setting of Kaho'olawe will draw from this description.

Geologic History

Kaho'olawe is a single shield volcano constructed chiefly of thin-bedded 'a'a and pahoehoe basalt poured rapidly from eruptions along a prominent rift zone extending west-southwest, and two other rift zones extending eastward and northward. A caldera, over 3 miles in diameter, borders the eastern portion of the island; at one stage in its geologic history, the caldera was completely buried. The island is approximately 1.5 million years in age, as derived from Potassium-Argon dates of rocks from Kaho'olawe (Naughton, MacDonald and Greenberg, 1980).

Structural information suggests that during the first phase of volcanism on Kaho'olawe, a broad shield was built with a summit vent on the east side of the island (Lua Makika). Lavas emerged from three major rift zones, with minor fire fountain activity producing thin deposits of pumice. The rapid construction of the lava dome was followed by the summit's collapse, producing the caldera on the eastern side of the island. The southwestward rift zone also collapsed, however, volcanic activity continued and the caldera and rift zone were eventually filled with lavas erupted from a few cinder cones (MacDonald, Abbott & Peterson, 1983 and Stearns, 1939).

Following volcanic activity, a long period of weathering ensued during which a thick mantle of soil developed, including A, B and C horizons (Hommon, 1980b; Stearns, 1939; Spriggs, 1987). Late volcanic activity, probably associated with post-erosional volcanic activity of Haleakala, resulted in additional dike intrusion and cinder cone eruption (Chen and Frey, 1985, Fodor et al., 1987).

During the hiatus between volcanic activity, sea level changed dramatically and in many places cut back the coastline of Kaho'olawe along weak fault lines. Dramatic examples include Kanapou and Kamohio Bays. Regional research conducted on the history of other islands in the Hawaiian chain indicates that all the islands were affected by a number of large landslides, and the steep cliffs and deep troughs on the southern side of Kaho'olawe may indicate potential landsliding in combination with normal faulting (see Figure 3.4).

Following late volcanic activity, alluvial materials derived from the weathering of Kaho'olawe were deposited in the major drainage bottoms. The thickness of these alluvial deposits at the stream mouth is unknown, but may range from 20-100 feet.

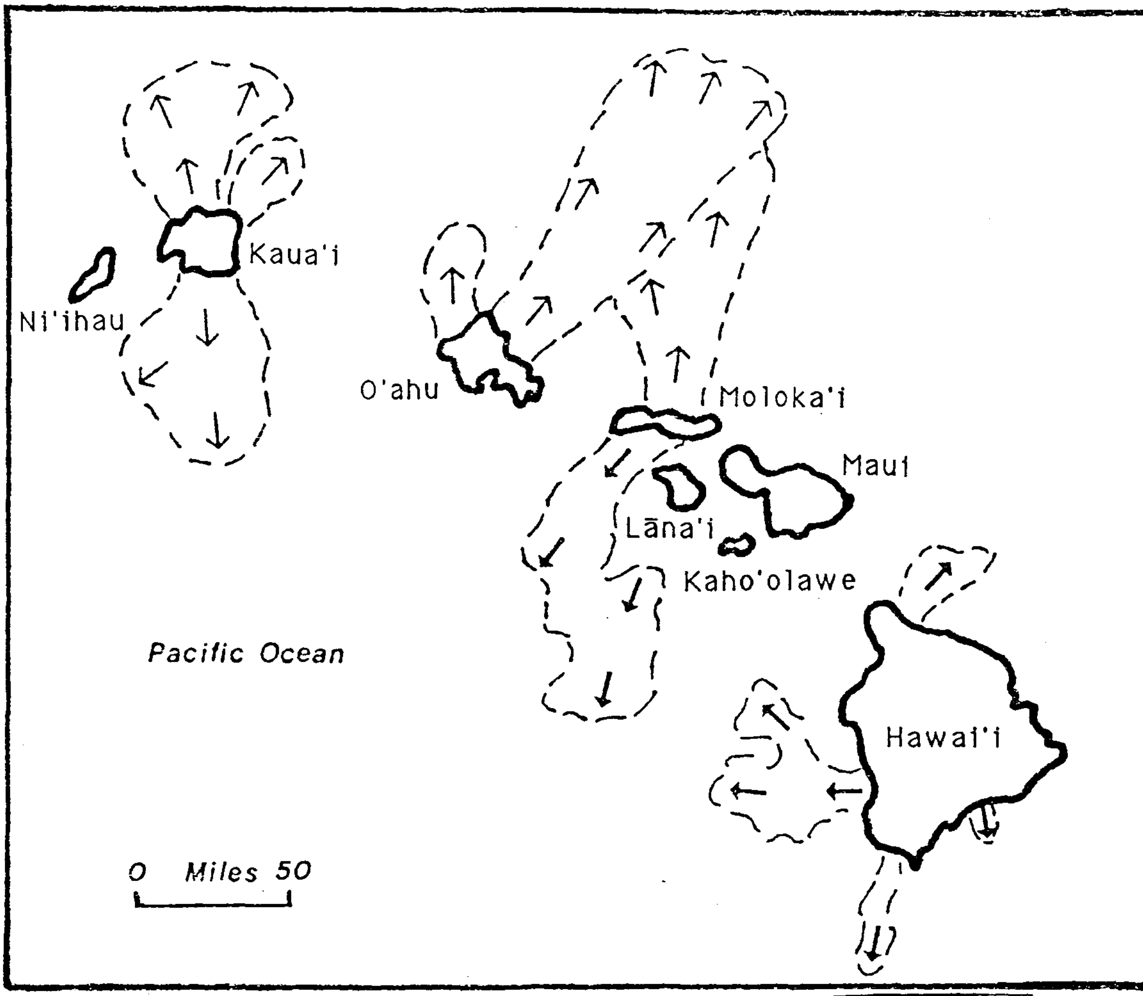


Figure 3.4. Map showing possible large scale landslides from major islands in the Hawaiian chain. The landslides are believed to have caused large tsunami waves. Stearns (1939) believed that a tidal wave was responsible for the deposition of sea shells in a cliff 800 feet above sea level on the southeastern shore of Kaho'olawe. The lack of a soil horizon on the south side of Kaho'olawe is also attributed to the removal of soil by a large tidal wave or tsunami.

Structure

In addition to the general identification of three major rift zones, numerous individual fractures and fracture zones on Kaho'olawe have been mapped in the field (Stearns, 1939). The west-southwest rift is marked by a broad ridge, and is dotted by the cinder cones Pu'u Moiwi and Pu'u Kamama, Lua Keaualalo and the collapsed crater Lua Kealialalo (see Figure 3.5). At one time, a graben extended along the west-southwest rift zone, formed as a result of the zone's collapse, and a trough about a mile wide and bounded by scarps at least 50 feet in height developed.[8] The north rift is indicated by the cinder cones Lua Kealialuna, Moa'ula, Pu'u Kolekole, and several spatter cone formations on the north shore mapped by Stearns in 1939. Field reconnaissance of the tributaries of Hakioawa gulch during the course of the present study confirmed structural displacement of rock units and fault controlled-features of the streambed, such as sharp bends, steep grades (98%) and abrupt changes in streambed level. The existence of three rift zones makes the presence of additional faults in the region likely.

The southern side of the island is marked by several normal faults in which the downthrown side is to the north. Examination of off-shore contours on the south side of Kaho'olawe reveals a deep trough extending south-southwest from Kamohio Bay, suggesting additional faulting present in this region.

Rock Types and Weathering Products

Stearns (1940) divided the rocks of Kaho'olawe into three groups, roughly indicative of their sequence of formation. They are: 1) shield-building lavas, 2) ponded caldera-filling lavas and post-caldera lavas and pyroclastic, and 3) "recent" materials (dikes and pyroclastic deposits younger than talus in the eroded caldera) implying post erosional emplacement. The lower lavas of the shield-building basalts are tholeitic, whereas the upper basalts are more alkalic, ranging in composition from olivine basalt to hawaiite.[9] The major difference in these rock types is the quantity of sodium, calcium, iron, and magnesium contained in each rock type. This affects the relative rate of weathering and the type of reaction product produced as a result of weathering.

Significant research on the part of many individuals, notably Goldschmidt (1954), Bowen (1956), Garrels and Christ (1965), and Helgeson (1975) has established the predictable sequence of weathering products from rocks of certain chemical compositions. The basic concept is:

Mineral + Water = Altered mineral + soluble reaction products

and suggests that given a certain rock type and information on the weathering rates and release of constituents that comprise the rock, it is possible to develop a framework for the evolution and secondary reaction products of a rock extruded at the earth's surface. Using this framework, it is also possible to identify the expected chemical composition of ground waters contained within weathered geologic units (Drever, 1982; Helgeson, 1968, 1969; Helgeson et al. 1969; Garrels and Christ, 1965).

Reaction products of rock weathering also affect the subsequent movement of water within the rock at a later date, and may also impact electrical resistivity surveys if salinity increases as a result of water storage within the rock (Wentworth, 1942; Zhody and Jackson, 1969, Norton, 1979, Drever, 1982).

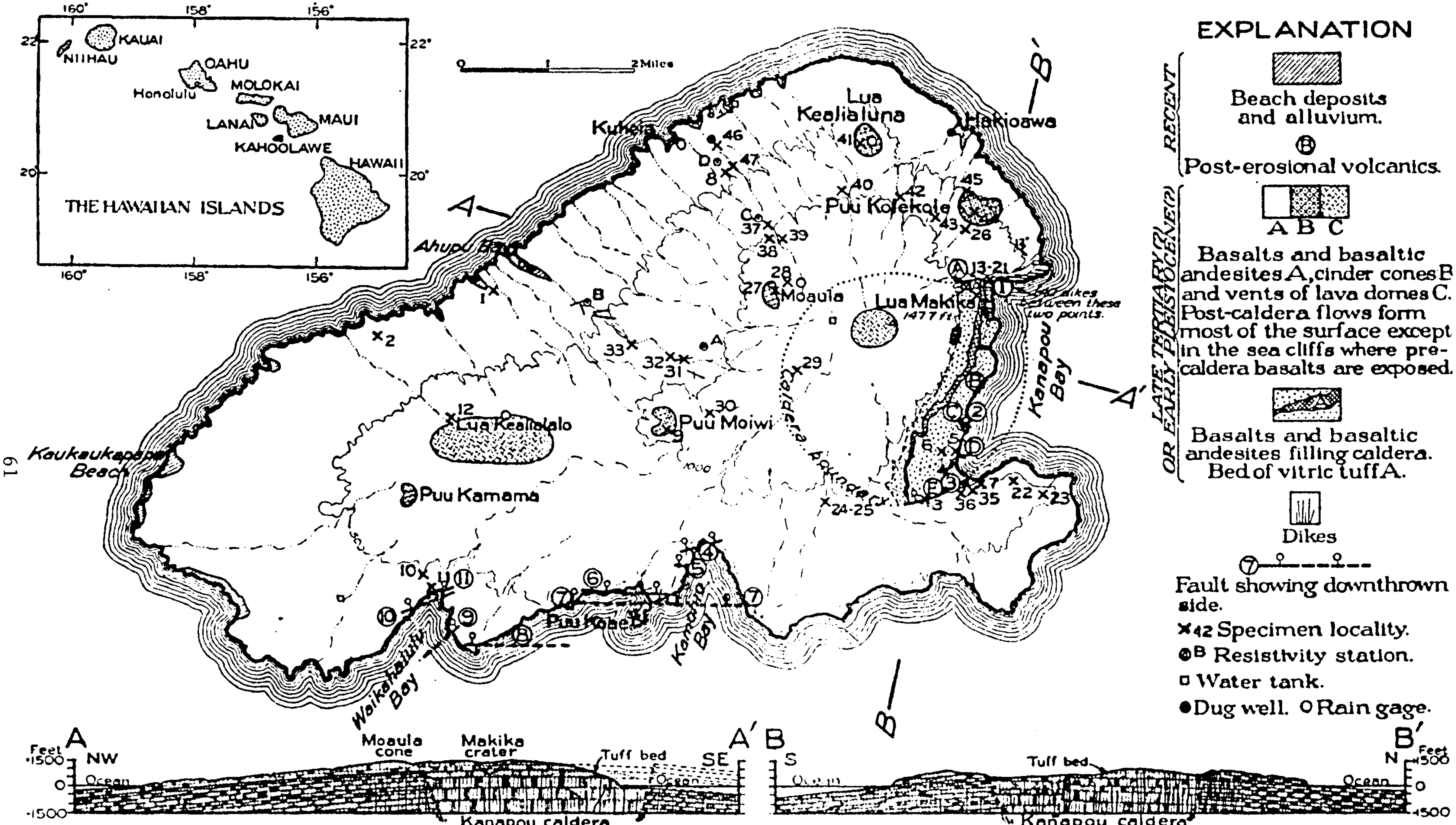


Figure 3.5. Harold Stearns' geologic map of Kaho'olawe (Stearns, 1940).

Rock types on Kaho'olawe are in one sense typical of Hawaiian basalts, but exhibit unusual chemical characteristics that imply secondary movement of hydrothermal fluids contemporaneous with and in later stages of island development. The consequent enrichment of particular elements (particularly Barium, Yttrium, and rare earth elements) as a result of hydrothermal alteration of Kaho'olawe basalts is not typical of regional basalts (Fodor et al., 1987, Chen and Frey, 1985), and may suggest a revision in current theories of both the age of Kaho'olawe and its relationship to volcanic activity on Haleakala (Clague, 1988, Chen and Frey, 1985). The presence of hydrothermal fluids as fluid inclusions at depth within Kaho'olawe also affects resistivity surveys and would act to decrease resistivity readings (Fodor, et al., 1987). Minor changes in abundance of certain chemical species, notably sodium, potassium, iron and magnesium, may have measurable impact on rates of weathering, erosion and the type of secondary weathering reaction products or rate of product formation.

Table 3.6 presents a summary of the major rock types on Kaho'olawe, their approximate range in chemical composition, and the major weathering products expected from decomposition by normal weathering processes. As can be seen, the major weathering product of Kaho'olawe basalts is clay, with the relative amount of leaching (i.e., availability of water) affecting the suite of clay minerals formed (Drever, 1982; MacDonald, 1983; Wentworth, 1942).

Summary

This chapter has presented descriptive information on the existing physiography, climate, vegetation, geology and soils of Kaho'olawe. The change in the hydrologic cycle--involving the increase of surface runoff as a result of the removal of vegetation and the decrease of infiltration--has created a difficult environment and difficult conditions in which to revegetate the island.

As a result of the geology of Kaho'olawe, the soil generated from the rock weathering includes a number of clay types that lead to a reduction in the hydraulic conductivity of soils. The removal of the soil cover also depleted the nutrient content of the remaining impoverished and vulnerable soils.

It is important to recognize this existing geological, physiographic, climatic and pedogenic history and framework inasmuch as this framework provides guidelines for further resource investigation and for island-wide environmental rehabilitation.

Table 3.6. Table of common rock types on Kaho'olawe and their major weathering products

Rock Type or Name	Weathering Potential[1]	Reaction Product[2]
Albite	1	• kaolinite (clay) • silica • sodium carbonate • smectite
Anorthite	1	• kaolinite • calcium carbonate • montmorillonite • allophane
Olivine	1	• limonite • hematite • silica
Magnetite	1	• limonite • hematite
Augite	2	• allophane • montmorillonite • hematite • silica • bauxite
Nepheline	2	• smectites • bauxite

Source: after Macdonald, Abbott and Peterson, 1968.

1 Reactivity according to Bowen's reaction series and Goldschmidt's extension to the breakdown and weathering of rocks.

2 The extent to which montmorillonite and other smectites are formed depends on geographic location and quantity of water leached through the soil or rock column.

Notes for Chapter 3

[1] H.. T. Stearns, Geology and Ground Water Resources of the Islands of Lanai and Kahoolawe, Hawaii, 1940, p.124. Records from four regional stations as reported by ranch hand Manual Pedro. These figures are only approximations as the amount of rainfall was estimated not measured.

[2] Data obtained from rain gage located at Hakioawa, records from October 1988 to January 1989.

[3] Fog was reported by Stearns, Kaho'olawe Field Notes, 1939; accounts of residents Ashdown, Recollections of Kaho'olawe, 1979, and reports by members of the Protect Kaho'olawe 'Ohana.

[4] The project gage station was installed by the U.S. Geological Survey in October, 1988. Data from the Hakioawa gulch station can be found in Table 3.1. The weather station installed by the Navy is jointly operated with the National Oceanic and Atmospheric Administration (NOAA). The station relays information via satellite to the data bank of the National Weather Service.

[5] Indirect peak flow measurements by the slope-area method (using Manning's equation) were completed for several reaches of Hakioawa gulch and its gully system. The calculations use the slope of the energy line (assumed parallel to the channel bed for purposes here), the hydraulic radius of the channel (obtained from observations of high water marks) a roughness coefficient estimated from field observations.

[6] Leaching of soils is inferred by the montmorillonitic-clay mixture in soils on the northeast and northwest portions of the island (soil samples analyzed by the Department of Geology, University of California, Berkeley, December 1988). Kaolinitic clays are dominant on the southern sides of Kaho'olawe.

[7] This list includes plants observed in a1980 botanical survey performed by Carolyn Corn, Winona Char, Gar Clarke and Linda Cuddihy for DLNR .

[8] Stearns, Geology and Ground Water Resources of the Islands of Lanai and Kahoolawe, Hawaii, 1940 and Macdonald, Petrography of Kaho'olawe, 1940.

[9] R. V. Fodor, G. R. Bauer, R. S. Jacobs, and T. J. Bornhorst, "Kahoolawe Island, Hawaii: Tholeitic, Alkalic and Unusual Hydrothermal 'Enrichment' Characteristics", 1987.

SECTION TWO

Surface and Ground Water Resources of Kaho'olawe

Introduction

The identification of the available supply of water on Kaho'olawe formed the central task of the Kaho'olawe water resources study. During the course of project work, the availability of surface water, both from runoff and from harvested rainfall, was calculated from Kaho'olawe watershed information, regional rainfall data, and field measurements of stream channel characteristics. The U.S. Geological Survey conducted an electrical resistivity and transient electromagnetic survey of selected portions of Kaho'olawe in the search for groundwater, and discovered a ground water body in the central northeastern portion of the island (Kauahikaua, 1988). Two watersheds were planned for instrumentation with hydrologic equipment, including continuous recording stream gage, rain gage and ground water level monitoring instruments.

This section reports the results of surface and ground water analyses conducted during the course of this study, and is divided into surface and ground water chapters. First, for surface water resources, the framework for analyses conducted--the watershed approach-- is discussed. Applications and results follow, including an analysis of Kaho'olawe's potential surface water supply. Records obtained from the stream gage and rain gage stations are presented and analyzed.

Next, for ground water resources, a description of the geophysical methodology and its application to Kaho'olawe is provided, including data regarding the hydrogeologic setting of the island and the location and identification of the ground water body discovered during the course of the project. Estimates of ground water supply are developed; however, the study concludes that a drilling program is necessary to evaluate overall yield. The section concludes with an overall assessment of island water resources.

Chapter 4

Surface and Ground Water Resources and Watershed Characteristics

Watershed Management: Toward a Framework for Water and Land Management on Kaho'olawe

Even a small island like Kaho'olawe poses formidable problems for the resource manager, and resource management strategies must be guided by a framework that logically and practically links land use with water use. The framework adopted in this project and report is that of the **watershed**, or **drainage basin**, which represents a logical unit of land and water resource management planning. Figure 4.1 presents two schematic outlines of a watershed. A **water balance** for each watershed on Kaho'olawe, which involves the relative input, disposition and output of water, forms the basis of water supply estimates.

Since water is the primary agent of sediment movement within watersheds, the analysis of the movement and occurrence of water on a watershed basis is key to the identification of land management needs. This perspective directly assists the protection of Kaho'olawe's natural and cultural resources, inasmuch as the stabilization of the current soil and water environment on Kaho'olawe assists in the stabilization of archaeological sites.[1]

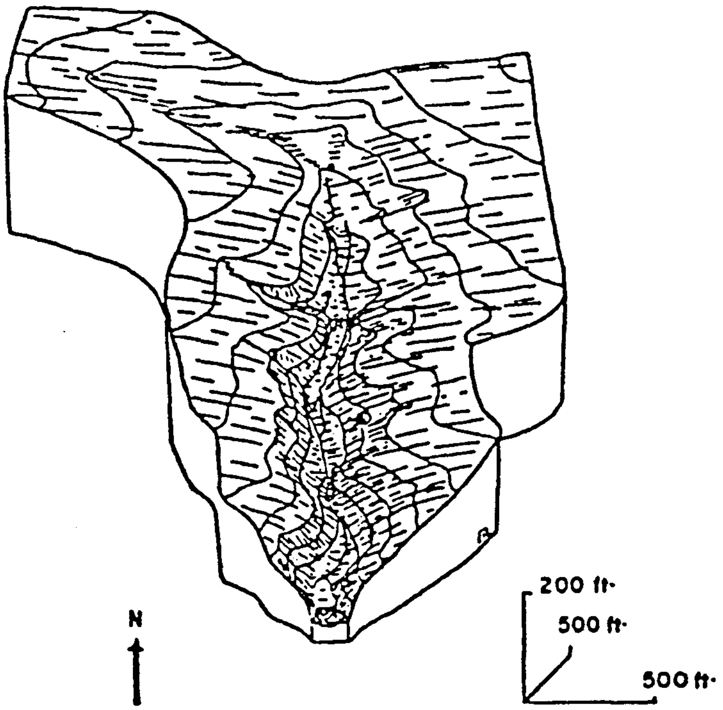
The Hydrologic Cycle

The hydrologic cycle describes the movement of water on and through the earth. The major elements of the cycle include: 1) *evapotranspiration*, which includes transpiration from vegetation and evaporation from open bodies of water and soil surfaces, 2) *precipitation*, 3) *infiltration*, 4) *runoff*, and 5) *deep percolation* to ground water. For the Hawaiian islands, this cycle is neatly completed with the discharge of fresh ground water to sea water through submarine springs. Figure 4.2 presents a schematic diagram of the hydrologic cycle for Kaho'olawe.

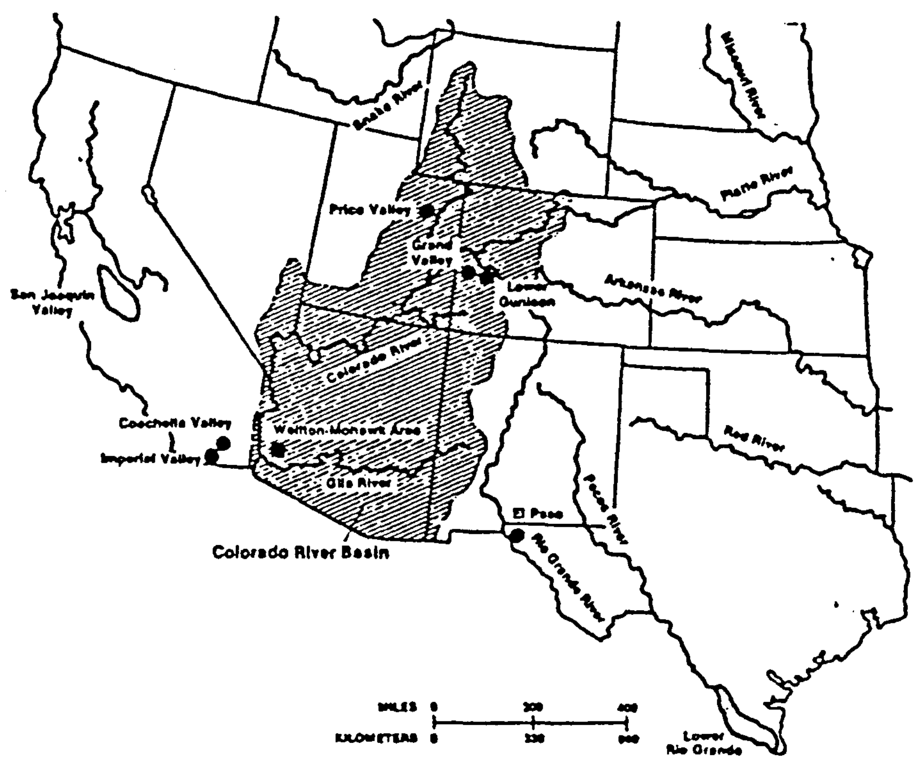
The principal task before the hydrologist is to quantify each element of the hydrologic cycle for the region of interest, in order to construct a water balance. This forms the basis for assessing needed inputs or management strategies, such as ground water recharge achieved through construction of small holding dams, or erosion control to facilitate runoff control.

The hydrologic cycle within a watershed forms the fundamental framework within which water supply is analyzed. In this framework, the surface water resource is the agent of erosion and transport of soil resources in the unit of a watershed, or drainage; the ground water resource within a watershed is either replenished within the watershed or discharged at some point, either into

Figure 4.1. Schematic diagram of two views of a watershed. Figure 4.1 (A) illustrates a subwatershed, while (B) illustrates a large watershed with many contributing rivers.



A
Block diagram showing topography of a watershed (Bricker, 1972)



B
The Watershed of the Colorado River Basin (Journal of Soil and Water Conservation, 1985)

subsurface alluvial materials lining channel bottoms or as springs in the offshore marine environment (see Figure 4.2). Overall water input (precipitation) is analyzed with the context of its distribution between evaporative demand, infiltration, deep percolation, and runoff, to arrive at an estimated quantity of water stored in or lost from the watershed.

The drainage basin, because it facilitates transport of both sediment and water, must also be seen as a geomorphic unit, in which the forces of gravity, water and sediment movement act to continually produce change within a drainage basin's channel shape, size, gradient, sediment load, and stream course. Land use in each watershed will impact these processes, simply by changing one or more of the elements which are part of the hydrologic cycle within each watershed. Balances long established by natural forces can easily be upset by factors such as the removal of vegetation and reduction of soil infiltration by trampling and result in an increase of surface runoff.[2]

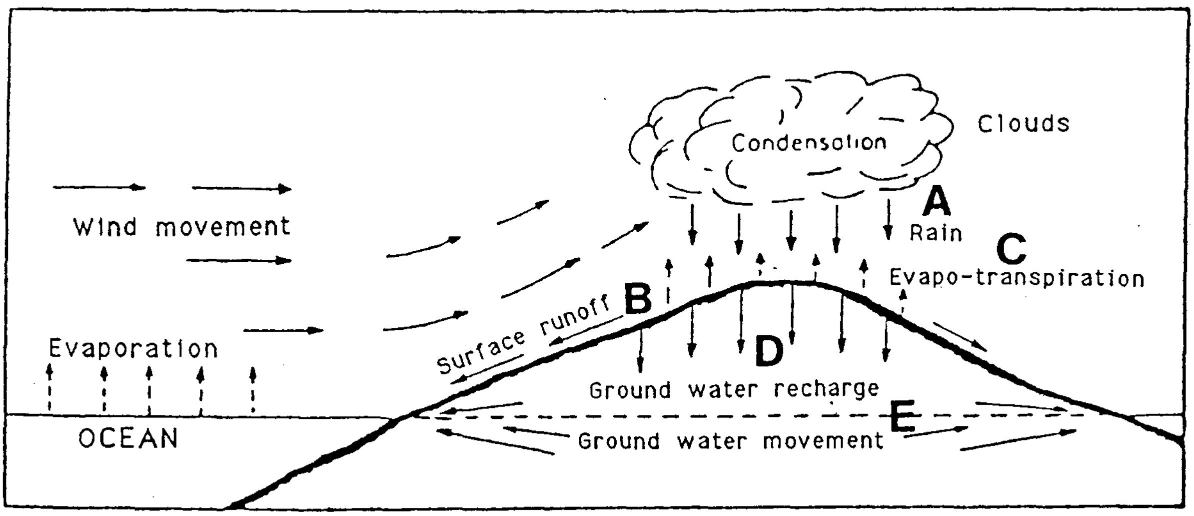


Figure 4.2. The hydrological cycle of a typical island in the Hawaiian chain. Precipitation (A) falling on the land surface is apportioned between surface runoff (B), evapotranspiration (C), infiltration (D), and deep percolation to groundwater (E). Eventually, much of the ground water resource is channeled to the ocean, where evaporation then occurs.

Drainage Basin Analysis, Kaho'olawe

The drainage basin may be defined as the area which contributes water to a particular channel or set of channels. It is the *source* area of the precipitation eventually provided to the stream channel by various paths. As such, it forms a convenient unit for the identification of water supply and for the consideration of the processes determining the formation of specific landscapes within a watershed, such as gully formation or "badlands" topography (Leopold and Miller, 1964).

Analysis of watersheds begins with examining the physical interrelationships between drainage area, stream length, and number of tributaries, and identifying the mechanisms of watershed evolution (i.e., water and sediment transport). Overall water supply is derived from an examination of the input of water to a watershed, its distribution among the various watershed components, and the output of water as measured at the mouth of the watershed. Table 4.1 presents a list of the descriptive parameters of watersheds as analyzed in this text.

A map of the watersheds comprising Kaho'olawe is presented as Figure 4.3. For the purposes of this study, the watersheds were clustered into quadrants (1, 2, 3, 4, counter-clockwise), superimposed upon the 1000 meter Universal Transverse Mercator (UTM) system, Zone 4 (Table 4.2). Watersheds are located according to the quadrant and UTM location of their headwaters. The figure reveals the orientation of the 63 watersheds.[3] Most watersheds radiate from Lua Makika, however, Pu'u Moiwi, Pu'u Kahua, Lua Kealialalo and Lua Keaualalo also serve as the headwaters of some important drainages. On the northern side of the island, Lua Kealialuna exerts major control over the formation and course of Hakioawa and Wa'aiki gulches (Figure 4.4).

Of the total 28,800 acres on Kaho'olawe, approximately 23,314 acres (81 %) comprise readily definable watersheds. The remaining 5,486 acres (19 %) occur as "interbasin lands:" at headwaters, as steep cliffs, and within craters and remnant cinder cones. The largest watershed, Ahupu Gulch, has an area of 2.56 square miles (1,638 acres); however, over 50 percent of all watersheds have areas considerably less, ranging between .1 and .4 square miles. Only 28 percent of Kaho'olawe's watersheds have areas over .9 square miles.

Table 4.1. Descriptive Parameters of Drainage Basin Analysis, Kaho'olawe, Hawai'i[1]

Name	Dimensions	Definition or Derivation
Stream Order	None	An integer designation of a segment of a channel according to the number and order of tributaries. (R)
Stream Number	None	Number of streams of a given length. (N)
Stream Length	Length	The distance along a stream channel. (L)
Average length of streams of a given order	Length	Where R is the given order. (L)
Bifurcation Ratio	None	Average ratio of number of streams (N) of a given order to number in next highest order, N/N.
Drainage Area	Length	Basin area contributing precipitation to a given channel segment.
Orientation	Degrees	Orientation of a watershed with respect to north-south-east-west coordinate plane.
Slope/Gradient	Percent/Degrees	Change in elevation along the channel length, watershed-wide and segment -specific. Also illustrated in profile.
Length of Overland Flow	Length	The distance over which water flows as sheet flow on the upper hardpan surface of the watersheds.
Other Parameters		Specific to research problems[2]

[1] Adapted from Leopold et al.,1964; reflecting Horton's 1941 original approach.

[2] Additional channel features are identified with respect to gully formation processes, including channel top width, bottom width, total depth, and stream channel longitudinal profile and slope (Heede, 1976; Horton, 1941).

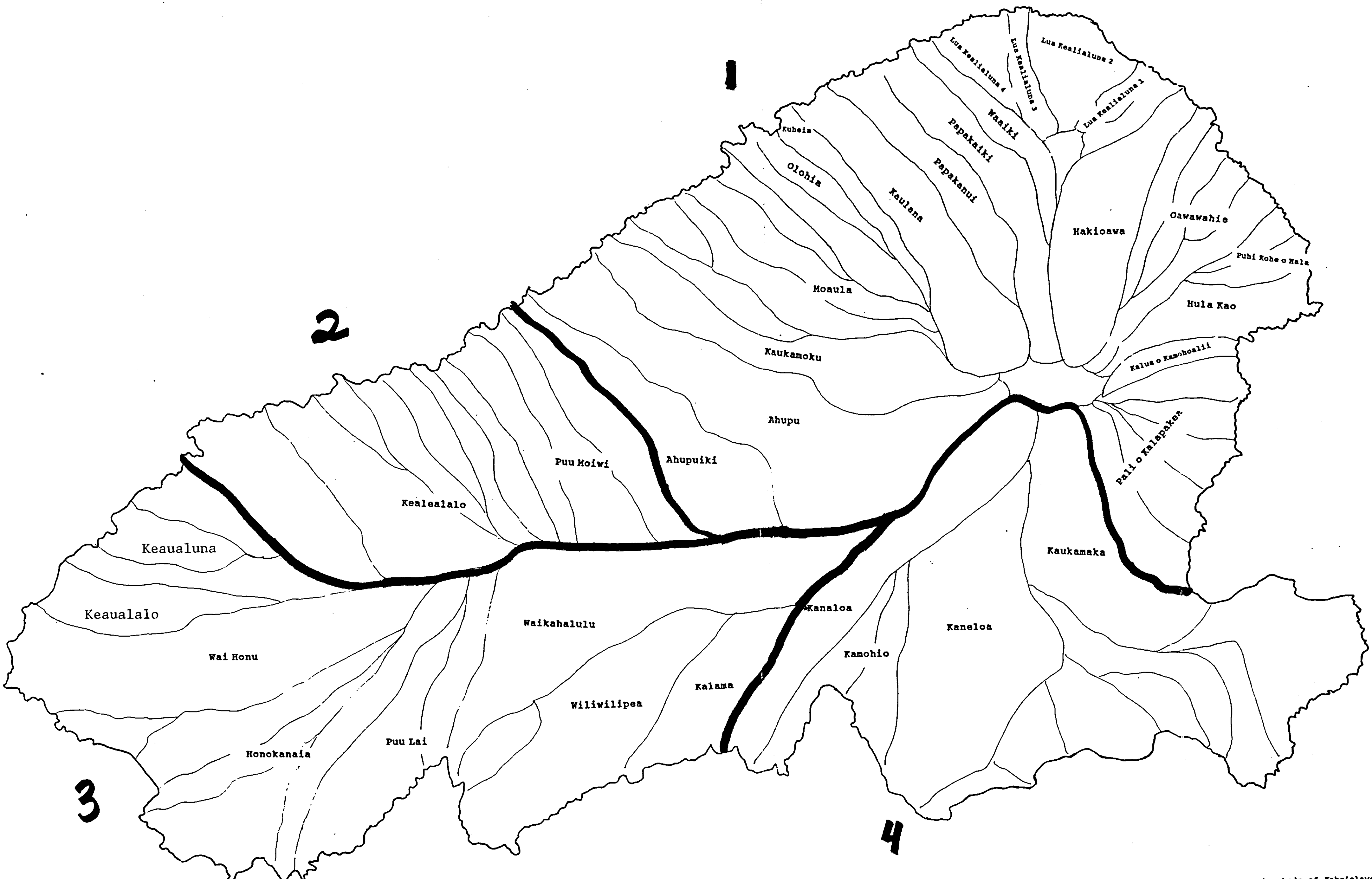


Figure 4.3. Map showing the 63 watersheds of Kaho'olawe. The map can be placed over the U.S. Geological Survey topographic map for additional reference. The largest watersheds originate in the east central portion of Kaho'olawe surrounding the summit at Lua Makika.

Demarcates Quadrants

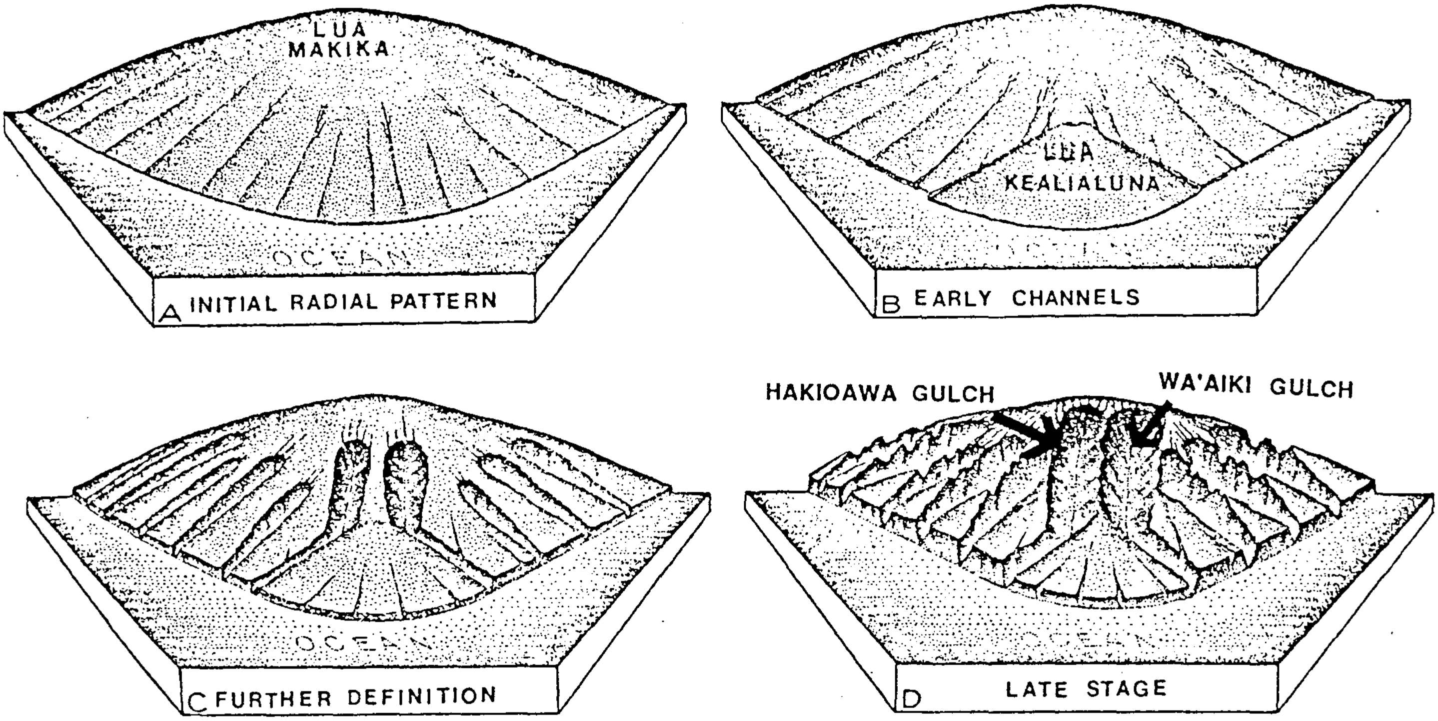


Figure 4.4. Diagram illustrating the effect of Lua Kealialuna on the development of the Hakioawa drainage basin. Lua Kealialuna acts to channel runoff to either side, creating unusually large and deep channels (Modified from Stearns, 1940 and Leopold, 1963).

Stream Channel and Drainage Basin Development

Information describing the drainage basin parameters of Kaho'olawe (as described in Table 4.1) is presented in Table 4.2. Data such as drainage area, length of streams, slope, stream order, and length of overland flow are tabulated. The information is useful in the evaluation of drainage basin development and in the development of resource management criteria. For example, the length of overland flow describes the length of surface over which water flows as a sheet. This process has significant implications for soil erosion (e.g., the length-slope factor in the Universal Soil Loss Equation) and is a major item to modify in overall soil erosion control strategies.

Stream order is a geomorphologic term which describes the number and type of streams in a drainage basin and defines the relative extent of drainage basin development. For example, Wa'aiki Gulch watershed has a single stream with no tributaries, and is a first order stream. Hakioawa Gulch watershed is a second order stream with three tributaries. For Kaho'olawe, 61 % (54 streams) of the drainage basins are first order basins, covering an area of 27 square miles, and 26 % of the

Table 4.2. Descriptive Parameters of Kaho'olawe Watersheds, 1989

WATERSHED NAME	Quad#	Drainage Area			Length	Altitude		Slope	Tribs	Stream Order	Overland Flow
	Map	Sq. Miles	Acres	Hectares	Miles	Feet	Meters	Percent	No. of		Miles
Hakioawa	1	1.180	755	306	2.00	1,213	370	11.5%	3	2	.65 mi
Lua Kealialuna 1	1	0.150	96	39	0.44	495	151	21%	0	1	NA
Lua Kealialuna 2	1	0.120	77	31	0.64	659	201	19.5%	0	1	NA
Lua Kealialuna 3	1	0.120	77	31	0.84	577	176	13%	0	1	NA
Lua Kealialuna 4	1	0.280	179	72	0.60	377.3	115	11.9%	0	1	NA
Wa'aiki Gulch	1	0.340	218	88	1.56	820	250	9.9%	0	1	.23 mi
Papakaiki Gulch	1	0.840	538	218	2.40	1247	380	9.8%	1	2	.91 mi
Papakanui Gulch	1	0.610	390	158	1.96	1115	340	10.7%	0	1	.50 mi
Kaulana Gulch	1	1.070	685	277	2.56	1312	400	9.7%	2	2	.73 mi
Kuhe'eia Gulch	1	0.356	228	92	1.20	738	230	11.6%	0	1	NA
Olohia Gulch	1	0.424	271	110	1.70	1017	310	11.3%	0	1	NA
Moaula 1	1	0.149	95	39	0.84	509	155	11.4%	0	1	NA
Moaula 2	1	0.057	37	15	0.36	196	60	10.3%	0	1	NA
Moalua 3	1	0.563	360	146	2.10	1197	365	10.8%	0	1	NA
Moaula 4	1	0.509	326	131	1.60	787	240	9.3%	0	1	NA
Moaula 5	1	0.289	185	75	1.52	682.4	208	8.5%	0	1	NA
Moaula 6	1	0.15	96	39	0.56	269	82	9.1%	0	1	NA
Kaukamoku Gulch	1	1.20	768	311	3.50	1381	421	7.4%	4	2	.54 mi
Ahupu Gulch	1	2.56	1638	663	3.60	1247	380	6.6%	4	2	1.34 mi
Ahupuiki Gulch	1	1.03	659	267	2.52	1017	310	7.6%	4	2	NA

Table 4.2. (Continued)

WATERSHED NAME	Quad#	Drainage Area			Length	Altitude		Slope	Tribs	Stream Order	Overland Flow
	Map	Sq. Miles	Acres	Hectares	Miles	Feet	Meters	Percent	No. of	Type	Miles
Pu‘u Moiwi 1	2	0.72	461	149	1.60	646	197	7.7%	0	1	NA
Pu‘u Moiwi 2	2	0.58	371	150	1.80	703	219	7.4%	1	2	NA
Pu‘u Moiwi 3	2	0.43	275	111	0.96	302	92	5.9%	0	1	NA
Pu‘u Moiwi 4	2	0.34	218	88	1.40	705	215	9.8%	0	1	NA
Kealialalo 1	2	0.25	160	65	0.60	289	88	9.1%	0	1	NA
Kealialalo 2	2	0.26	166	1667	0.64	328	100	9.7%	0	1	NA
Kealialalo 3	2	0.33	211	85	0.20	124	38	11.8%	0	1	NA
Kealialalo 4	2	0.14	90	36	0.32	164	50	9.7%	0	1	NA
Kealialalo 5	2	1.10	704	285	1.40	640	195	8.7%	1	2	NA
Kealialalo 6	2	0.76	486	197	1.00	341	104	6.4%	0	1	NA
Keaualuna 1	3	0.35	224	91	0.84	236	72	5.3%	0	1	NA
Keaualuna 2	3	0.34	218	88	0.84	213	65	4.8%	0	1	NA
Keaualuna 3	3	0.49	314	27	1.30	367	112	5.4%	0	1	NA
Keaualalo 4	3	0.51	326	132	0.68	98	30	2.7%	0	1	NA
Wai Honu Gulch	3	1.98	1267	513	2.80	617	188	4.2%	0	1	NA
Honokanai‘a 1	3	0.66	422	171	1.16	390	119	6.4%	0	1	NA
Honokanai‘a 2	3	0.62	397	161	0.76	236	72	5.9%	0	1	NA
Honokanai‘a 3	3	0.58	371	150	1.40	492	150	6.6%	0	1	NA
Pu‘u Lai Gulch	3	0.37	237	96	0.40	528	161	25%	0	1	NA
Waikahalulu Gulch	3	2.30	1472	596	4.00	1053	321	4.9%	2	2	NA
Waikahalulu Gulch 2	3	2.00	128	52	.60	459	140	14.5%	0	1	NA
Wiliwilipeapea Gulch	3	1.57	1005	407	2.20	443	135	3.8%	0	1	NA

Table 4.2. (Continued)

WATERSHED NAME	Quad#	Drainage Area			Length	Altitude		Slope	Tribs	Stream Order	Overland Flow
	Map	Sq. Miles	Acres	Hectares	Miles	Feet	Meters	Percent	No. of	Type	Miles
Kalama Gulch	3	0.69	442	179	1.00	846	258	16%	0	1	NA
Kanaloa Gulch	4	1.65	1056	427	3.8	1371	418	6.8%	0	1	.53 mi
Kamohi'o 1	4	0.36	230	93	0.40	889	271	42%	0	1	NA
Kamohi'o 2	4	0.19	112	45	0.64	951	290	28%	0	1	NA
Kaneloa 1	4	0.26	166	67	0.44	715	218	30.7%	0	1	.78 mi
Kaneloa 2	4	0.50	320	130	1.28	1000	305	14.8%	0	1	NA
Kaneloa 3	4	0.25	160	65	0.84	512	156	11.5%	0	1	NA
Kaukamaka Gulch	4	1.57	1005	406	1.84	1174	358	12%	1	2	1.4 mi
Pali O Kalapakea 1	1	0.54	346	140	1.24	1036	316	15.8%	0	1	.62 mi
Pali O Kalapakea 2	1	0.31	198	80	0.76	984	300	25%	0	1	.43 mi
Pali O Kalapakea 3	1	0.22	141	57	0.64	1154	352	34%	0	1	.30 mi
Pali O Kalapakea 4	1	0.21	134	54	0.60	1148	350	36%	0	1	.52 mi
Pali O Kalapakea 5	1	0.24	154	62	0.68	1148	350	32%	0	1	.40 mi
Kalua O Kamohoali'i	1	0.18	115	47	0.92	1296	395	26.6%	0	1	NA
Hula Kao Gulch	1	0.83	531	15	1.04	984	300	18%	1	2	.65 mi
Puhi Kohe O Hala 1	1	0.37	237	96	1.48	1154	352	14.7%	0	1	.42 mi
Puhi Kohe O Hala 2	1	0.12	77	31	0.64	715	218	21%	0	1	.42 mi
Oawawahie 1	1	0.37	237	96	1.48	1154	352	14.7%	0	1	.65 mi
Oawawahie 2	1	0.17	109	44	0.56	623	190	21%	0	1	NA
Owawahie 3	1	0.25	160	65	1.20	1000	305	16%	0	1	.41 mi
Oawawahie 4	1	0.27	173	170	1.20	951	290	15%	0	1	.81 mi

basins (9 streams) are second order streams, covering an area of 12 square miles, with the remaining area classified as interbasin land as described above.

The bifurcation ratio indicates that there are 6 times as many first order as second order streams. This suggests a relatively undeveloped drainage network that evolves primarily through headward extension of tributaries, a process common to many Hawaiian island watersheds. However, evidence of rill development, advance of gully headcuts and mass-wasting of gully sideslopes suggest an increased dissection and continued development of watershed features in both lateral and headward directions. As expected, the second order streams drain the largest watersheds, all of which have their origins on the most barren portion of the island. These watersheds must therefore generate the largest amount of runoff.

Overall slopes of stream beds are steep on Kaho'olawe, ranging from 5 % to over 42%. There is considerable variation along the course of each streambed, with slopes of 75 % not uncommon. Some drainages end as spectacular waterfalls into the ocean below, particularly on the east and southern sides of Kaho'olawe.

The positions of the remnant crater, vents and subsurface rift structures are expected to have major influence on the development of the drainage network. In addition, drainage basin evolution by "capture" of one stream channel by another is a major evolutionary process on Kaho'olawe, especially in selected areas of Kaho'olawe's northern side.

Stream capture exerts a considerable influence on the resulting distribution of streamflow and mass-wasting within watersheds on Kaho'olawe. For example, several northern tributaries of Hakioawa gulch are presently advancing, through headcut erosion, toward the major drainage of Wa'aiki Gulch, which drains a major portion of the hardpan area (see Figure 4.4). Additional runoff captured by and channeled through Hakioawa gulch as a result of Hakioawa tributaries "capturing" Wa'aiki gulch would result in increased dissection of the land surface and would alter the physical shape of the channel and the present base camp at the mouth of Hakioawa gulch. Inasmuch as headward advancement of streams is an apparently rapid process on Kaho'olawe at this time, potential stream capture literally marks the threshold erosive conditions which signal Kaho'olawe's present instability.[4]

Stream Profiles and Cross Sections

A series of selected stream channel profiles are presented for Hakioawa Gulch (Figure 4.5). The profiles are representative of typical conditions found on the northeastern end of the island. The Hakioawa profile illustrates the structural control of the stream channel.

As a stream evolves, it seeks to find a base level to which it will cut the stream bed. Sea level is base level for streams in the Hawaiian islands, however, local base level control may develop. For example, the numerous lava flows poured in succession from the vents of Kaho'olawe in the construction of the shield volcano produced several bedrock ledges which may be considered local base levels that affect stream channel evolution, in addition to the overall sea level control. Dike swarms may also serve as local base level. Some of these bedrock ledges are shown in the profiles illustrated in Figure 4.5, and lend a stair-step configuration to many gulches. These features become important in siting erosion control structures that seek to stabilize the gully gradient in an effort to stem the tendency of gullies to downcut the channel. Check dams and other structures can be effectively established on local bedrock ledges.[5]

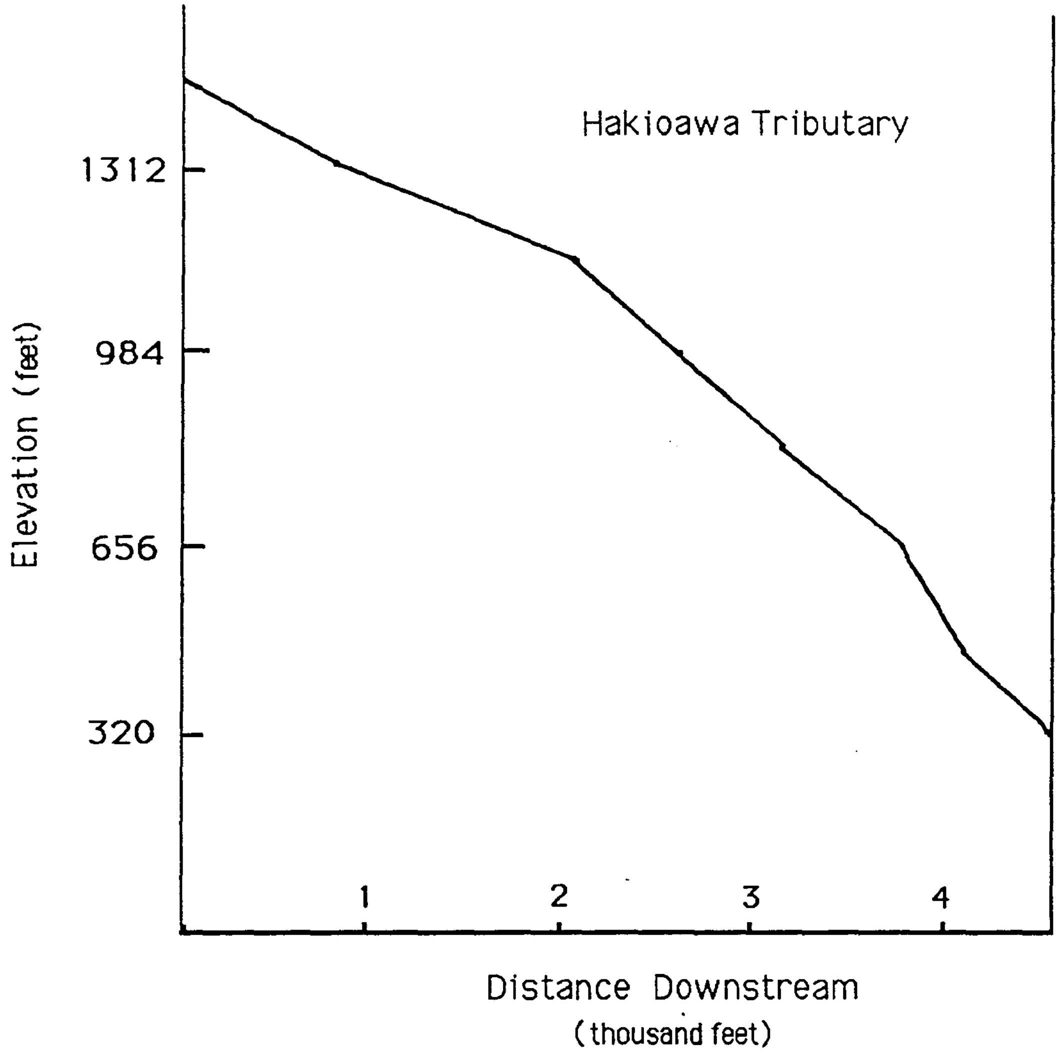
Summary and Implications of Drainage Basin Analysis for Resource Management on Kaho'olawe

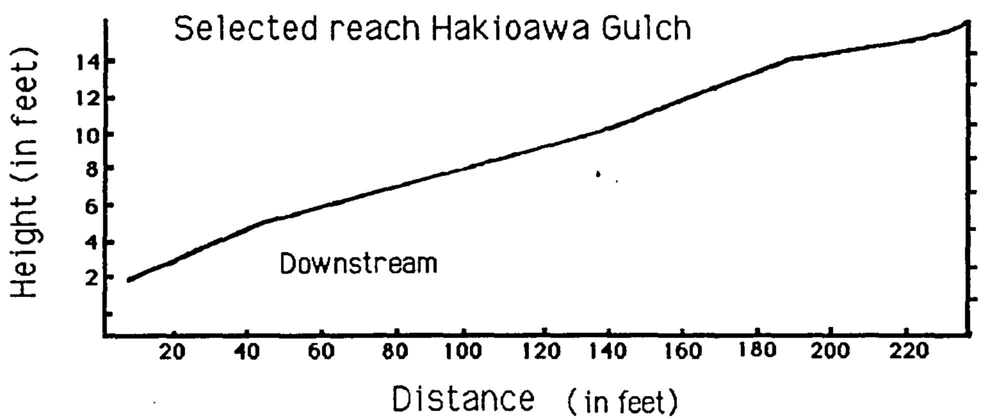
The watersheds of Kaho'olawe have channel cross sections that indicate their capacity for transmitting large quantities of surface water after each storm, and channel geometry information collected can be used on Kaho'olawe to verify stream flow values retrieved from gage stations. Channel storage is minimal inasmuch as bedrock forms a considerable portion of the channel bottom in most watersheds. Channel banks consisting of easily erodible soil material and non-competent weathered bedrock in excess of 75 feet in height form the primary sediment load of streams. Overall drainage basin development is in a headward direction; however, lateral extension of gully side slopes is occurring both through bank undercutting and through mass-wasting of side slopes.

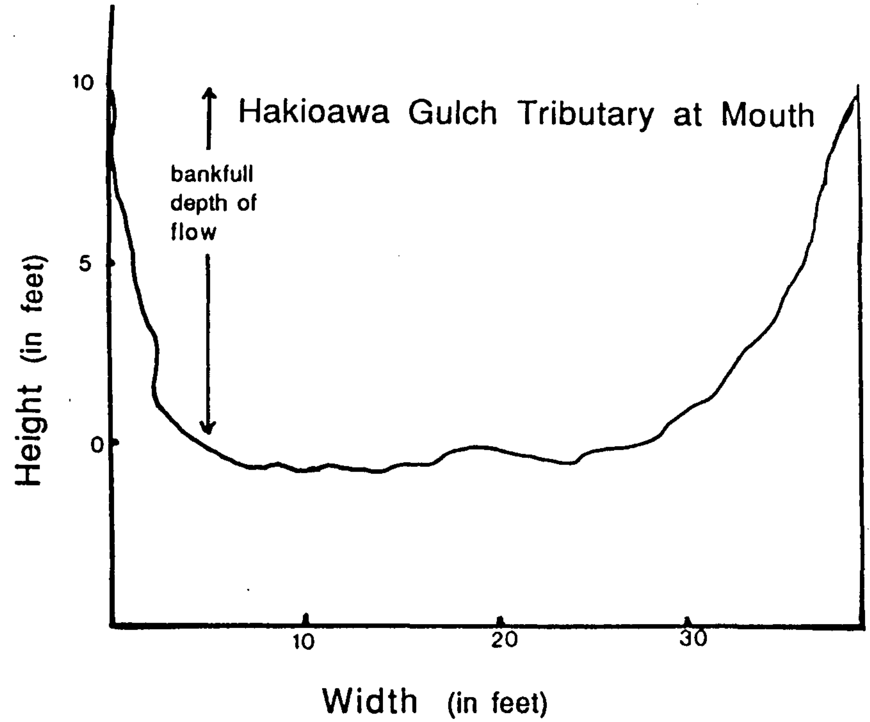
Resource conservation efforts on Kaho'olawe, taken in this light, must necessarily focus on the headward advance component of gully evolution and seek to stabilize gully and channel side slopes using local bedrock levels as bases for the construction of check dams.

Table 4.2 was used in the Kaho'olawe water study as a basis for establishing criteria for the selection of watersheds most critically in need of resource management work.

Figure 4.5. Stream channel profiles and cross sections for selected reaches and tributaries of Hakioawa Gulch.







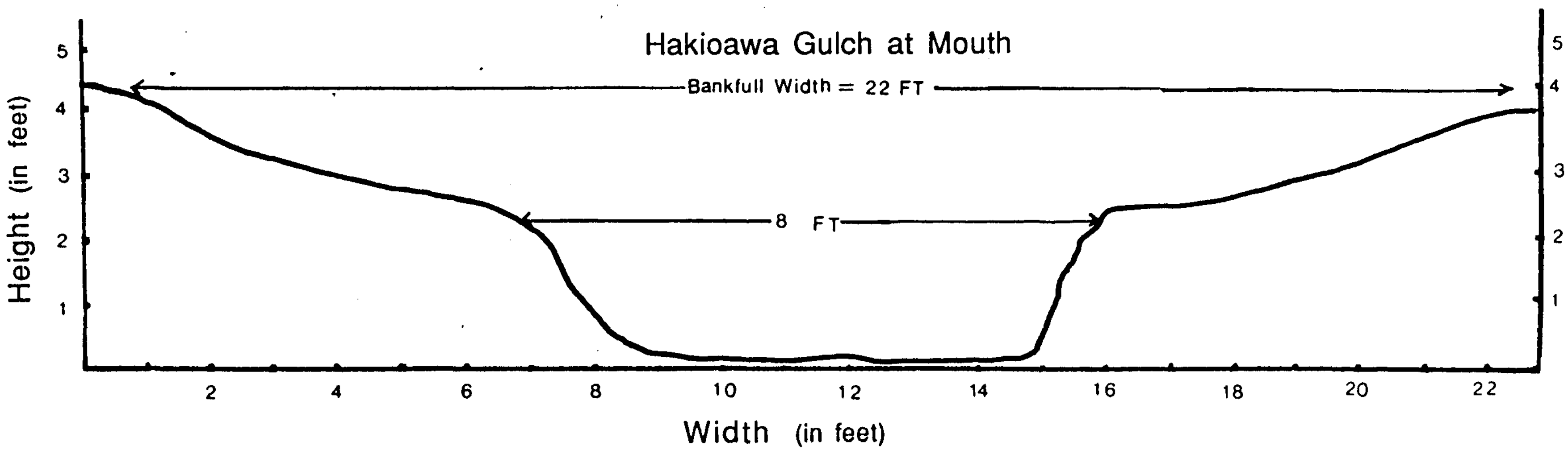


Figure 4.5. (Continued)

Surface Water Resources

The analysis of surface water hydrology begins with an estimation of water supply derived from precipitation, and then moves to an evaluation of runoff characteristics of the landscape derived from the properties of soils and the characteristics of watersheds. Inasmuch as there is a paucity of soil, rainfall and runoff data for Kaho'olawe, estimates of rainfall amount, duration and intensity, and estimates of runoff, must be derived from regional rainfall and runoff records for selected localities on Maui and Lana'i having the same general climatic and soil characteristics as Kaho'olawe.

Water Supply: Precipitation

As indicated in the physiography section of this report, the rainfall data are not complete for the island of Kaho'olawe. Even though rain recording stations have existed on Kaho'olawe from 1919-1939 and from 1970-present the gage stations have not been properly maintained. Consequently, rainfall characteristics, such as amount and intensity, are derived from rain stations at certain locations on Maui and Lana'i having similar climatic characteristics as Kaho'olawe (see Table 3.1). Rainfall records from the stations at Kihei, Kaumalapau Harbor and Ulupalakua Ranch, and limited soil analyses for these locations, all on the lee side of Haleakala and at various elevations, were analyzed for the period 1970 to the present and data used to develop annual rainfall estimates for Kaho'olawe.

Although rainfall on Kaho'olawe is expected to be greater on the summit than on the shore and, in certain times of the year, is expected to be greater on one side of the island than the other, as with other Hawaiian islands, there is simply no information that would allow the development of a detailed rainfall distribution map for Kaho'olawe. In 1975, the Hawai'i Water Resources Study team developed a rainfall distribution map for Kaho'olawe; however, the data does not reflect true conditions of Kaho'olawe. For example, the rainfall map indicates a relatively low rainfall amount for coastal regions, on the order of 8 inches. However, in 1988, during a period of 3 months, data was collected that indicated a total of 15 inches was received near the coast, with individual storms producing as much as 7 inches of rainfall in a 24-hour period. This is nearly twice the amount indicated on the rainfall distribution map, and suggests the direction of the storm front may have more to do with the total amount and distribution of rainfall than elevation. Figure 4.6 shows an approximate distribution of rainfall for Kaho'olawe based on the Hawai'i Water Resources map and data from the Kaho'olawe Water Study.

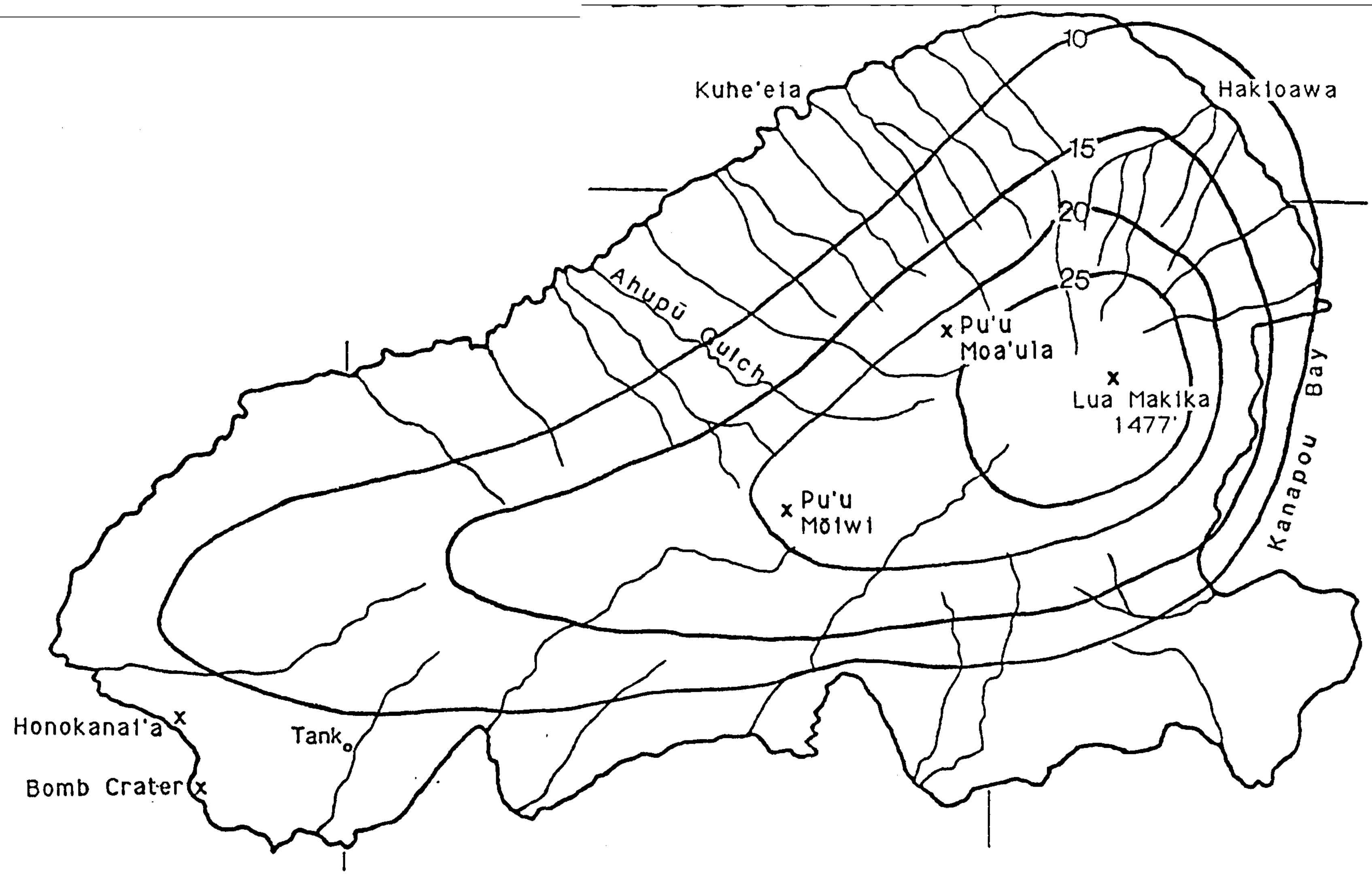


Figure 4.6. Map showing the approximate distribution of rainfall on Kaho'olawe. As discussed in the text, the distribution of rainfall on Kaho'olawe is not strictly a function of elevation, but has more to do with direction of the storm front and watershed orientation (After Hawaii Water Resources Regional Study, 1979).

Other factors indicate the distribution of rainfall on Kaho'olawe is not necessarily tied to elevation. For example, *kona* storms are widespread and produce island-wide rains for many of the Hawaiian islands. Secondly, watershed orientation and minor topographic features might produce a micro-variation in rainfall amounts which would be important to vegetation zones, water supply calculations, and runoff estimates. The often shifting direction of the wind in the channel between Maui and Kaho'olawe can mean the difference between completely dry or very wet winter and spring conditions.

The deficiency of this information for Kaho'olawe, resulting from failure to operate and maintain the existing gage network, is disappointing; however, a rough estimate of the quantity of water input to each watershed on Kaho'olawe based upon total annual rainfall and watershed acreage is presented in Table 4.3. Of the 19 billion gallons of rain that falls on Kaho'olawe for a year in which there are 25 inches of rainfall, the majority of runoff occurs in the larger watersheds on the northern part of the island which have their origin around Lua Makika.[6] Hence Ahupu, Hakioawa, Kaulana, Ahupuiki, Waikahalulu and Wai Honu gulches receive the greatest amount of rainfall from individual storms; because of the barren nature of these watersheds' headwaters, these same watersheds generate the greatest amount of runoff for individual storms.

Table 4.3 Gross Quantities of Water Supplied to Selected Kaho'olawe Watersheds in an Average Year of 25 inches of Rainfall[1]

Watershed	Location[2]	Drainage Area (in acres)	Supply (in acre feet)	Supply[3] (in gallons)
Hakioawa	1	755	1,573	512,640,700
Wa'aiki	1	218	454	147,958,600
Kaulana	1	685	1,427	465,059,300
Kuhe'eia	1	228	475	154,802,500
Ahupu	1	1,638	3,407	1,110,341,300
Ahupuiki	1	659	1,307	425,951,300
Wai Honu	3	1,267	2,635	858,746,500
Honokanai'a	3	422	877	285,814,300
Waikahalulu	3	1,472	3,061	997,579,900
Kaukamoku	4	1,005	2,090	681,131,000

[1] Assumes even distribution of rainfall over the entire island.

[2] Quadrant number from Table 4.2. See figure 4.3 for location on island.

[3] One acre foot = 325,900 gallons

Of particular interest is the total amount of rainfall expected for certain kinds of storms, for example, the 2 year, 24-hour storm. The National Weather Service has developed maps of storm types and amounts of rainfall (in inches) for all the Hawaiian islands except Kaho'olawe. Information from the neighbor island stations mentioned above were used in estimating the amount of rainfall for each storm type on Kaho'olawe. Table 4.4 presents these values.

As seen in the table, estimated rainfall quantities were supplemented with data obtained from the rain gage installed during the course of this project at the mouth of Hakioawa Gulch. Figure 4.7 presents rainfall hydrographs, illustrating the high intensities of Kaho'olawe rains. During the course of the project, the maximum intensity recorded was 1.6 inches per hour for a storm on November 4, 1988.

Table 4.4. Rainfall Amounts for Different Storm Types, Kaho'olawe

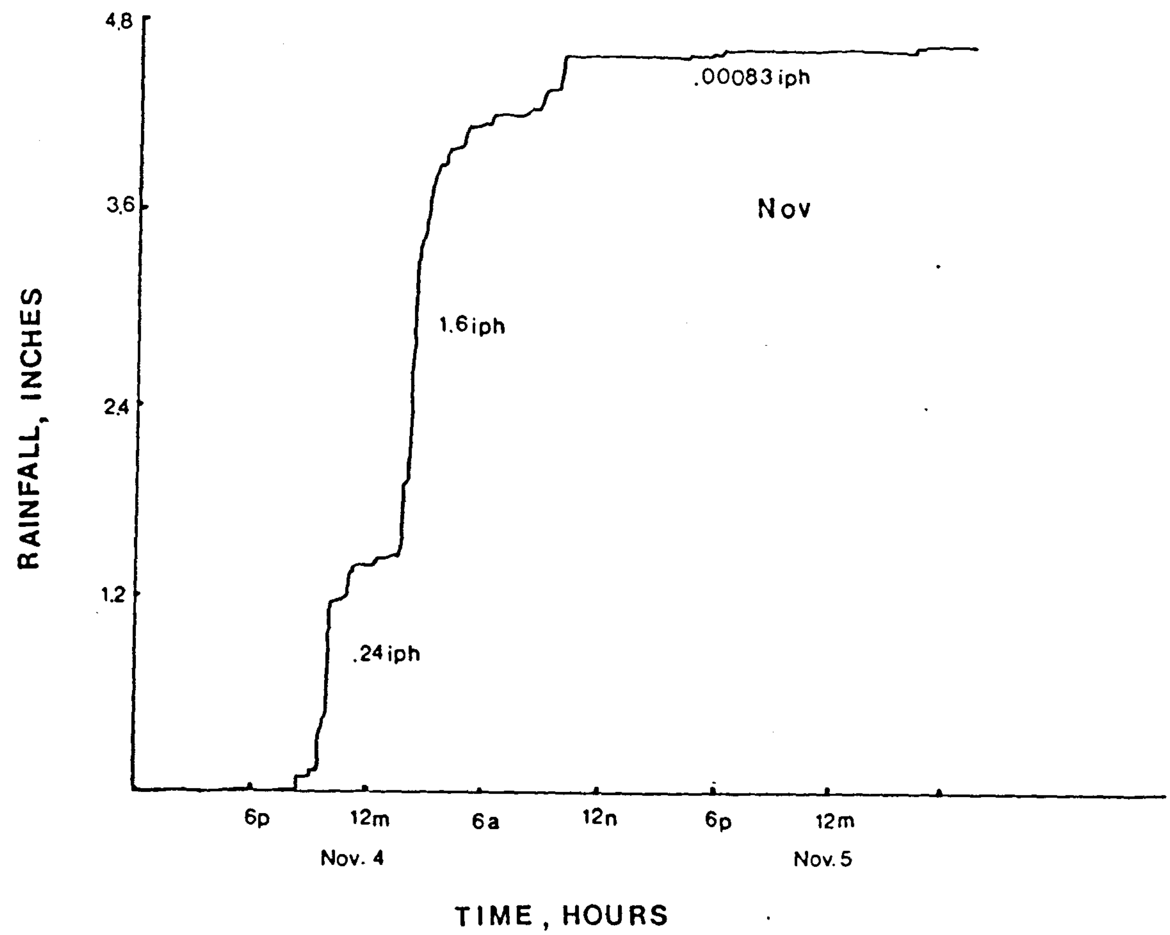
Storm Type	Rainfall Amount[1] (in inches)	Actual Recorded Rainfall Amounts[2] (in inches)
2 year, 24 hour	3-4	3.4" on 11/4/88
5 year, 24 hour	5	
10 year, 24 hour	6-7	
25 year, 24 hour	7-8	7.26" on 12/6/88
50 year, 24 hour	8-9	
100 year, 24 hour	10-12	

Source: National Weather Service maps in U.S. Soil Conservation Service, 1981, p.83-88.

[1] Range of values extrapolated from contours for stations identified in text and applied to Kaho'olawe.

[2] 24 hour storms recorded at the rain gage installed during the course of the Kaho'olawe Water Study at Hakioawa. Record presented and discussed in text.

Figure 4.7. Rainfall record of the storm of November 5, 1988, as recorded at the mouth of Hakioawa Gulch. Note the high intensity of the storm, a characteristic of most Kaho'olawe rains. The bursts of rainfall were mirrored--with little time lag--by the streamflow record at the station in Hakioawa Gulch.



Storm of November 4-5, 1988

Time : 31 hours
24-Hour Precipitation: 3.4 "
Total Precipitation: 4.7 "
Intensity
Maximum: 1.6 iph
Minimum: .24 iph

Surface Runoff

Runoff is that portion of the hydrologic cycle which describes the movement of incident precipitation over the land surface and into and through the stream channel. Water may move as overland flow (or sheet flow) to stream channels or as subflow moving under the soil surface for eventual delivery to the channel (Figure 4.2). There are no perennial streams on Kaho'olawe and runoff occurs only in response to rainfall.

However, for Kaho'olawe, runoff from even small rainfall events is a critical factor in the hydrologic cycle, inasmuch as runoff is usually accompanied by large soil losses and extensive damage to roads and facilities on the island. Moreover, large areas of a presently barren surface, the hardpan, generate significant quantities of runoff and provide the physical surface that generates highly erosive water velocities. Control of runoff is therefore a critical element in the stabilization of the soil, vegetation and water environment on Kaho'olawe.

This section uses three well-known methods to estimate runoff from Kaho'olawe's watersheds, and supplements this information with indirect and direct streamflow measurements of Hakioawa gulch taken during the course of this project. The three methods are those developed by the U.S. Soil Conservation Service, the slope area method with application of the Manning Equation (Chow, 1964), and the method of the U.S. Geological Survey as applied to small watersheds in Hawai'i (Wau, 1969). Estimates of runoff for Kaho'olawe are estimates developed for peak flow, and the total quantity of runoff is estimated from an annual water balance perspective.

The U.S. Soil Conservation Service (herein referred to as SCS) developed a method for predicting peak rates of flow from small agricultural or rangeland watersheds. The factors of the SCS analysis which control runoff on Kaho'olawe include:

1) Total amount, intensity and duration of rainfall, which determines its erosive character,
2) Soil surface conditions and properties,
3) Antecedent moisture conditions,
4) Vegetation cover and type, and
5) Land use and/or conservation practices.

The total amount, intensity and duration of rainfall is usually obtained from analysis of rainfall records for the area of interest. If rainfall intensity exceeds the infiltration capacity of soils, runoff will occur. Antecedent moisture conditions reflect the amount of rainfall a watershed has received 5 days prior to the period of analysis and affects the soil moisture reserve and the consequent ability of soils to receive more moisture through rainfall. Naturally, if the soil is saturated, no additional water may sink in and runoff from the watershed increases. The SCS method used here reflects *average* conditions of antecedent moisture, however, runoff values for different antecedent moisture conditions can be obtained.

Soil surface conditions, percentage covered by vegetation and land use practices are factored into the runoff equation by the use of a number of tables developed by the SCS. Hydrologic soil groups have been established which broadly characterize the soil's response to rainfall; that is, the infiltration capacities of the soil. The Kanepu'u and Lahaina soil series of Lana'i were used for the purposes of this study (Whitesell,1971) and are considered clay-loam soils with highly erosive character. Classification of vegetation cover is based strictly on the percent of vegetative cover and the condition of cover (i.e., grazed or ungrazed). Finally, the type of land use practice adopted refers to the combination of vegetative cover and the type of land use treatment-that is, whether the land is terraced, contoured or in row crops, whether grazing lands are rotated, and a number of other factors.

Using the factors identified above, peak runoff rates for selected watersheds on Kaho'olawe were calculated. Table 4.5 presents the SCS information identified for selected Kaho'olawe watersheds representing a range of island conditions. The runoff estimates, which range from 500 cubic feet per second to 1,000 cfs, were computed for three storm types: the 5 year, 10 year and 25 year 24 hour storms, and are presented in Table 4.5.

Table 4.5. Peak runoff estimates for selected Kaho'olawe Watersheds Using the SCS and Manning Approaches[1]

Watershed	Soil Conservation Service Method[2]			Manning Equation[3]
	5-year	10-year	25-year	
Hakioawa	530	832	992	554.2
Ahupu	858	1,352	1,617	650.5*
Kaulana	505	780	933	420.8*
Kuhe'eia	192	296	355	150.2*
Wai Honu	606	936	1,119	509.5*

1 Values in cubic feet per second

2 Based on 5, 10 and 25 year storm amounts.

3 Based on field measurements of channel geometry, determination of hydraulic radius, slope, roughness coefficient and area.

* Estimated values for Manning equation parameters.

Inasmuch as the SCS method can only be considered a rough approximation for Kaho'olawe, other methods were used to develop estimates of peak flow, including the use of the Manning Equation (Chow, 1964) in the slope-area method applied to Hakioawa gulch. The Manning Equation,

$$V = \frac{1.49\ R^{2/3}\ S^{1/2}}{n}$$

where:

V = velocity (feet/second),

R is the hydraulic radius in feet,

S is the slope of the energy line,

n is the roughness coefficient of the channel, specifically known as Manning's n.

Values of n were obtained from Barnes (1967) using field descriptions as measured during the course of the project. This equation was used in the slope-area method to develop estimates of peak flow. These values are also shown in Table 4.5.

Finally, field measurements taken in December, 1988, and streamflow records of Hakioawa gulch obtained from the island's first stream gaging station installed in October, 1988, reveal additional peak flow information. Hydrographs of streamflow obtained from the stream gaging station are presented as Figure 4.8.

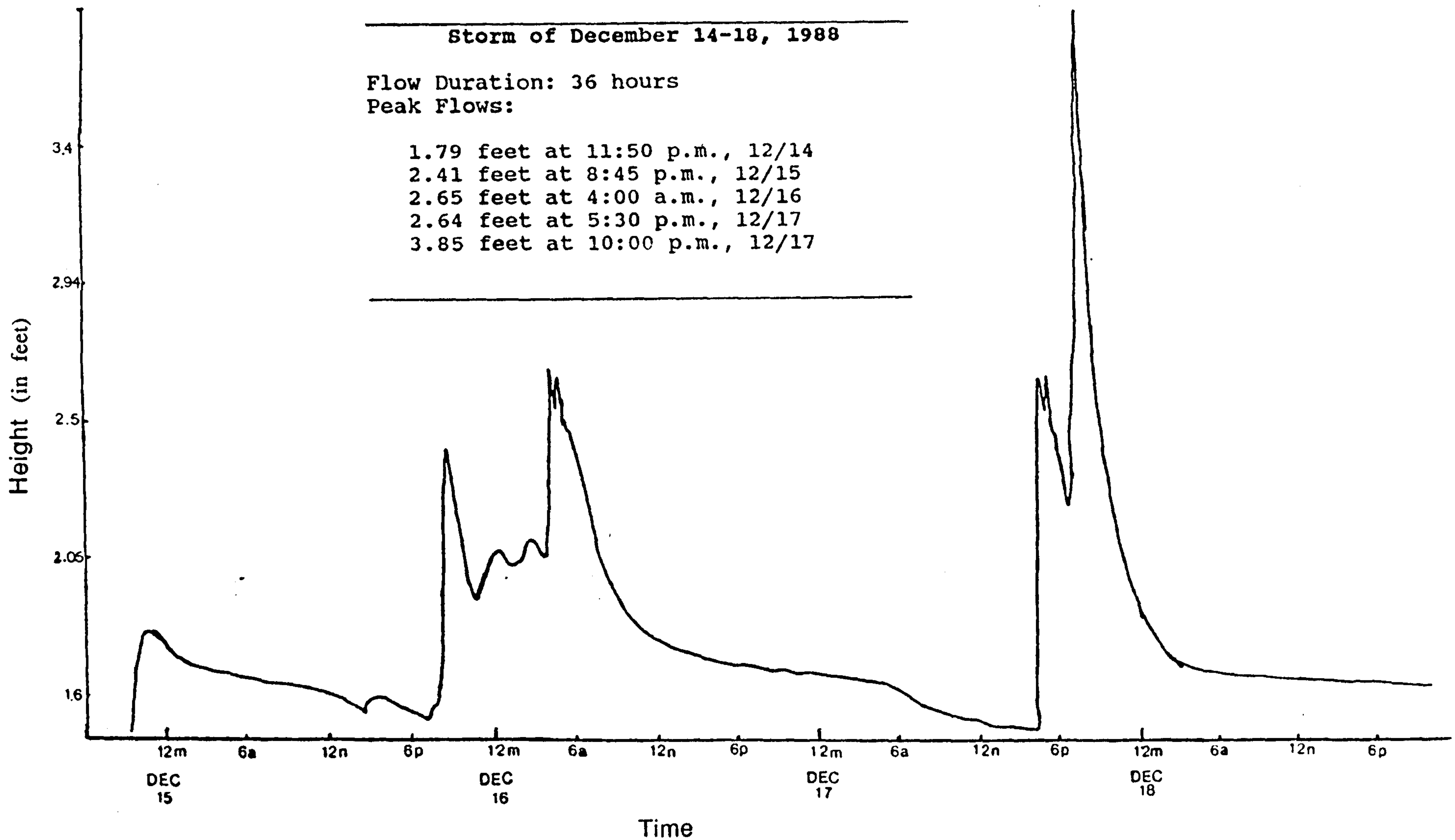
Streamflow hydrographs reveal that flows on Kaho'olawe are "flashy", with watersheds exhibiting rapid response to rainfall events. In one sense, this is quite characteristic of many Hawaiian streams.[7] Examination of the raingage and streamflow records together (Figures 4.7 and 4.8) reveals this relationship (short time of concentration), with the highest intensity storms producing the highest peak flows. The rapid response to rainfall, even after prolonged drought, suggests a very low infiltration capacity of Kaho'olawe soils and little channel storage. Indeed, many soil surfaces on the island have been observed to seal even after minor rainfall events as a result of the significant clay content of soils coupled with moderate or light intensity rains. Infiltration rates of one inch per hour are highly unlikely. The lack of vegetation cover leads to the reduction of infiltration capacities of the soil, and also contributes to the high runoff rate and volume.

The high sediment load of Kaho'olawe flows attest to the large scale erosion occurring all over the island. The stream gage installed in the Hakioawa Gulch had to be dug out after the storm in November, 1988 with over three feet of sediment collecting in the gage house well itself. Streamflow approaches 80 percent fine sediment in many places. Watershed conditions as reflected at the stream gage are poor, with high erosion rates, frequent flooding, and significant non-point source pollution of streamflow.

In summary, these calculations reveal that a considerable amount of water moves from the highlands to the coast through the channel beds and banks. Those watersheds producing the greatest amount of runoff have their origin in the barren eroded area surrounding Lua Makika. As vegetation was removed on Kaho'olawe, it is likely that runoff increased to the point observed and measured today, where nearly all rainfall is returned to the sea as runoff.

Further research in small watershed hydrology on Kaho'olawe would be beneficial to the understanding of land use impacts on flood peaks, overland flow and sediment transport. In the context of continued resource conservation work on Kaho'olawe, hydrologic change as a result of beneficial practices could be measured with such instruments as the stream gage at Hakioawa. This would be useful to the development of basic data and watershed parameters for hydrologic equations and models specific to Hawaiian island hydrology.

Figure 4.8. Rainfall records for the storms in December, 1988, as recorded by the rain gage at the mouth of Hakioawa Gulch.



Water Demand: Evapotranspiration

Evaporative demand on Kaho'olawe depends upon a complex combination of several factors, including the growth stage and type of vegetation, wind speed and direction, air temperature, humidity, and the percent of direct sunshine the land receives during each month. Additionally, soil type and the distribution of moisture within the soil reserve impacts the total quantity of water that can be evaporated. The orientation of each watershed is an important factor because it determines the relative exposure of watersheds to the climatic factors that impact water supply.

Because of the lack of research regarding climatic conditions on Kaho'olawe, there is little site-specific information regarding any of these factors, especially evaporation. Estimates of evaporation from the drier islands in the Hawaiian chain range from 40 percent of rainfall to over 70 percent of rainfall (Todd, 1983, and Hawaii Water Resources Regional Study, 1979). Research in Hawai'i, primarily by the sugar and pineapple industries, show that, although evapotranspiration differs widely from place to place, annual variations at any one place are small. To develop estimates of evaporation, the relation of rainfall to pan evaporation and evapotranspiration, recognized by Cox (1954), is often used as a tool. Pan evaporation data in relation to rainfall from stations on Maui and Lana'i, in addition to research regarding transpiration of different vegetation types, were used to develop broad estimates of evaporation from Kaho'olawe.

There are several different vegetation types on Kaho'olawe, with different evapotranspiration demands. *Kiawe*, for example, has been linked to the reduction of ground water recharge and thus increasing salinity of ground water on Kaho'olawe (Stearns, 1940). Roots of *kiawe* trees may extend up to 60 feet below the land surface and one single tree may transpire as much as a half foot of water per day (or 1000-2500 millimeters/year).[8] The water consumption of kiawe, based on these figures and *kiawe* water use data can be estimated by determining the area of coverage of *kiawe* groves. This method, and additional research, can be applied to the estimate of evapotranspiration requirements of tamarisk trees, which are planted extensively on Kaho'olawe. Evapotranspiration data for Kaho'olawe are presented in Table 4.6.

Evaporation from the bare soil on Kaho'olawe is significant as a result of the large barren exposure of soil surfaces in combination with high winds. Moreover, high soil temperatures resulting from the lack of cover combine to produce a difficult environment in which to re-establish vegetation. Without supplemental water, vegetation strategies in this environment may suffer large losses. Evaporation data estimated for bare soils on Kaho'olawe are also presented in Table 4.6. As derived from the table, evapotranspiration consumes approximately 25% of the total precipitated water supply.

Table 4.6. Evaporation data for Kaho'olawe calculated from climatic, soils and vegetation data. *

Evaporative Parameter	Evaporation Amount (inches/day)	Comment
Evapotranspiration		On an annual basis, this amounts to approximately 21% of total evaporative demand & of total available rainfall.
Kiawe	.6	
Tamarisk	.8	
Grasses & shrubs	.2	
Evaporation		Accounts for 4% of total evaporative demand.
Bare Soil	.3	
Pan Evaporation	Not available	
Total Inches Per Day	1.9	
Total Converted to Billion Gallons per Year	5.2 billion gallons/year	25% of total water supply

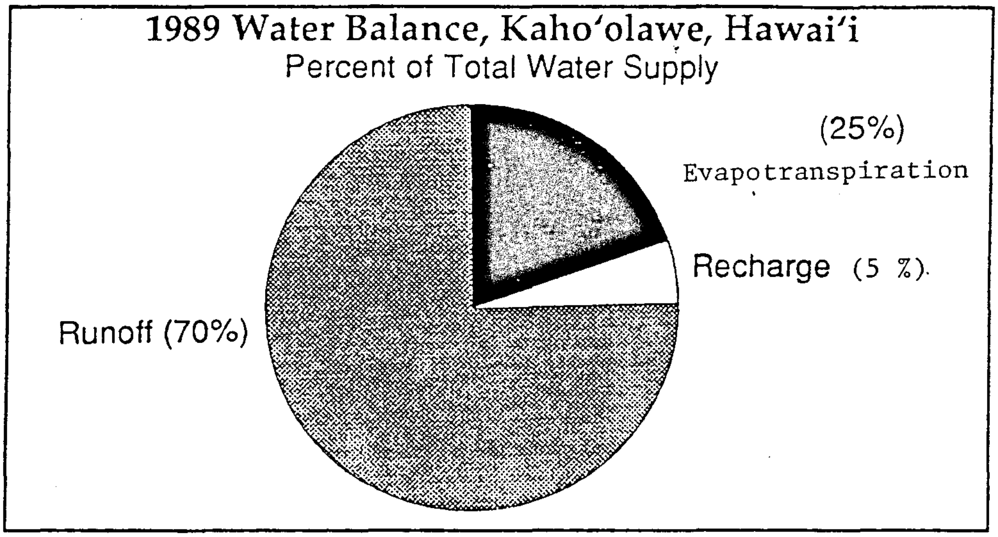
*Sources: U.S. Department of Agriculture, Soil Conservation Service, 1979; Hillel, 1971; University of Hawaii Agricultural Extension Service, 1989; and Takasaki, 1978.

Water Balance Calculations

Having identified the major components of the hydrologic cycle on Kaho'olawe, it is possible to approximate a water balance for the island's watersheds. As indicated in Figure 4.9, at the present time, evapotranspiration consumes nearly 25 % of the total surface water supply, with nearly 70 % of the supply occurring as runoff. Water infiltrating as recharge to the ground water resource, discussed in the next chapter, accounts for the remaining 5 % percent of the overall annual water supply.

Approximately 13.3 billion gallons of water escape as runoff to the ocean on Kaho'olawe on an annual basis. Early Hawaiian occupation took advantage of streamflow at the mouth of Ahupu and Kaulana, where terraces, small diversions and dug wells are found. Island residents in the post-1920's, responding to a changing ground water environment, took advantage of streamflow by constructing rock-walled diversion structures and large-capacity cisterns. Gradual siltation of these structures occurred as the vegetation cover of the upper watershed was removed and erosion followed. An increasing amount of silt at the mouths of the gulches brought by streamflow derived from the eroding hardpan may have affected recharge of fresh water to the ground water supply.

Figure 4.9 presents a comparison of water balance calculations for the year 1989 and how the water balance might have appeared in 1700, before the introduction of goats and other livestock. Note the significant percentage increase in runoff and the concomitant decrease in recharge. While the amount of evaporation has remained consistent, the nature of the process has changed. In 1700, evaporation occurred primarily through transpiration from the diverse island vegetation. Evaporation today occurs primarily from the bare soil of the hardpan surface and through transpiration from the dominant *kiawe* and tamarisk trees.



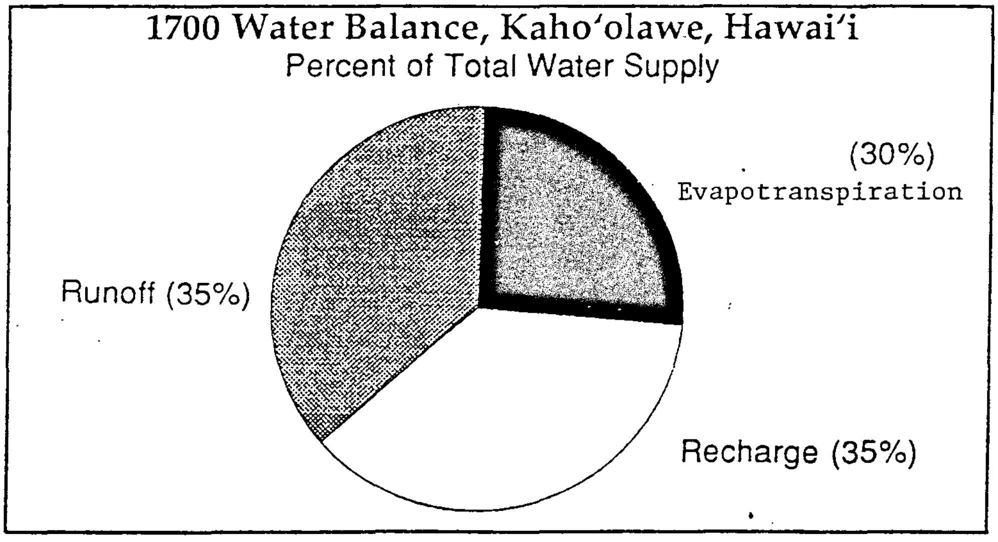


Figure 4.9. Diagrams showing the water balance of Kaho'olawe as computed in 1989 and showing the likely balance in the year 1700 (before grazing). The major difference is the increase in runoff and the concomitant decrease in recharge in 1989 as compared to previous centuries. While runoff may have been only 35% of the water balance in 1700, 1989 figures suggest runoff approaches 70% of the water balance.

Notes to Chapter 4

1 In the past, wind erosion was seen as the primary erosive agent on Kaho'olawe. While wind still plays an important role in soil erosion and landscape change on Kaho'olawe, the role of water erosion has gone largely unacknowledged, primarily because of the prevailing myth that Kaho'olawe is barren, without water. Yet, the large sculpted gullies which encircle the island's perimeter attests to the work of water as a powerful erosive agent.

2 H. T. Stearns, Geology and Ground Water Resources of the Islands of Lanai and Kahoolawe, Hawaii, 1940 estimated that over eight feet of topsoil was lost from approximately 15,000 acres of the island's summit.

3 Full sized copies of this map are on file at the Division of Water and Land Development, Department of Land and Natural Resources, State of Hawai'i and can be overlaid on the U.S. Geological Survey map for elevation relationships of watersheds.

4 Erosion rates approaching greater than one foot per year were confirmed by field placement of erosion pins at selected gully heads, September, 1988. Rapid change at all field sites was recorded over the duration of the project.

5 B. H. Heede, "Engineering Techniques and Principles Applied to Soil Erosion Control,"1968.

6 The figure of 19 billion gallons of rain during an average year of 25 inches of rainfall is derived using the formula where 1 acre = 1 acre foot if the land were covered by 1 foot of water and 1 acre foot=325,900 gallons. 25 inches of rain = 2.1 feet or 25/12. Multiplying 25/12 x 28,800 acres (total island acreage) = 60,000 acre feet x 325,900 gallons = 19,554,000,000 gallons per year. This assumes an even amount of rainfall across the island.

7 Richard Nakahara, Hydrologist, U.S. Geological Survey, Honolulu, Hawai'i. Personal communication with C. Vandemoer, December, 1988.

8 T.E.A. Van Hylckama, Weather and Evapotranspiration Studies in a Salt-Cedar Thicket, Arizona, 1980. As an example of the amount of water consumed by vegetation, consider an area of 10 acres covered completely with *kiawe* forests, with each tree consuming a half a foot of water per day. The calculation of quantity is:
10 acres x .5 feet of water/day = 5 acre-feet per day
5 acre feet/day x 325,900 gallons/acres foot = 1,629,500 gallons per day.
Clearly, water loss through evapotranspiration is a significant component of any water calculation.

Chapter 5

The Ground Water Resources of Kaho'olawe

Introduction

A major component of the Kaho'olawe Water Study was an island-wide investigation of ground water resources. The study was conducted by the Geophysics and Water Resources Branches of the U.S. Geological Survey and was completed in January 1989 (Kauahikaua, 1989). The purpose of this section is to describe the hydrogeologic setting of Kaho'olawe, the geophysical work that was completed, and the results of the investigation. Further ground water work for Kaho'olawe is proposed in Section 4 of this report.

Ground water, or water occupying the voids within and between the rocks below the land surface, is a vital resource in Hawai'i. Roughly, 90 percent of all domestic uses Statewide is satisfied by ground water. For Kaho'olawe, the existence of ground water provides the source of critically needed water for revegetation and island stabilization purposes. However, there is much to be learned from further investigation and comprehensive planning of a drilling program, including potential yield and water quality.

The setting and context for the evaluation of ground water resources and solution of practical problems on Kaho'olawe is linked to the application of advancements in volcanic island hydrogeology made in the last century (Fujimura and Chang, 1981; Lau, 1981; Meinzer, 1942; Stearns, 1939, 1940, 1942). For example, regional scientists have identified the general hydrogeologic setting and characteristics of volcanic terrains, thus providing the researcher with broad guidelines useful to the design of ground water investigations.[1] The development of exploration tools, such as the application of geophysics to the location of ground water, provides the analyst with a variety of methods to apply to any given situation. The development of the Ghyben-Herzberg relation, which describes the relationship between sea water and the freshwater head within an aquifer, is an additional useful advancement in hydroscience applicable to the present study of Kaho'olawe's ground water.[2]

Previous Work

The first major investigation of the ground water resources of Kaho'olawe was conducted by Harold Stearns in 1939. In addition to the broad hydrogeologic reconnaissance that was conducted, Stearns cites an electrical resistivity study of a northeastern portion of Kaho'olawe (Figure 5.1) conducted by G. R. MaCarthy that identifies a thin lens of ground water standing between .5 and 1.5 feet above sea

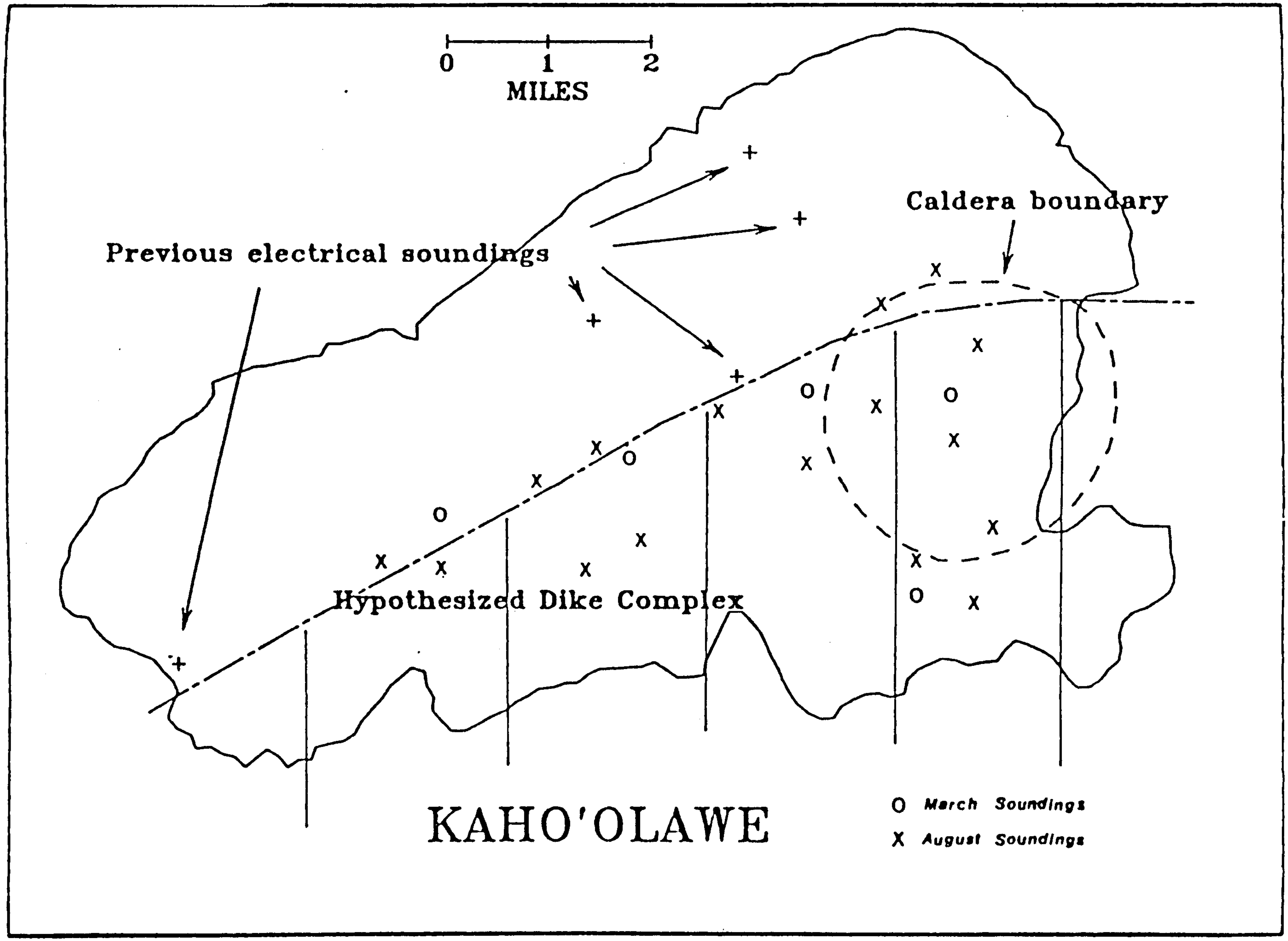


Figure 5.1. Map showing the location of electrical resistivity survey points on Kaho'olawe as conducted by MaCarthy in 1939. (Modified from Stearns, 1940).

level. Stearns also identified a number of dug wells on the island in the mouths of gulches, which early Hawaiians inhabitants placed near the walls of the gulches. Stearns hypothesized that these wells derived water from basalt, not alluvium, and that recharge occurred at higher elevations and moved within the rocks or between the many layers of basalt poured out over the landscape. Through field work, the author also identified two seeps in the cliffs of Kanapou Bay, measuring the yield of one at .25 pint/minute. These and many other known springs have long since disappeared. Significantly, Stearns notes that "sweet water was derived from the well (at Ahupu Bay) until about 1917," implying change was occurring to the ground water resource. He concludes by stating that a well, drilled near the headwaters of Ahupu Bay at elevation 1250 feet, might encounter the dike complex and possibly ground water.[3]

One of the most significant contributions of the Stearns report was the identification of three major rift zones and the presence of large-scale faulting on Kaho'olawe. The rift zones are marked by a number of dikes, which are features that can impound or compartmentalize ground water. This information, coupled with knowledge of rock types, implies the existence of a structure on Kaho'olawe capable of containing ground water. The rift zones and associated faulting are shown in Figure 5.2.

In 1965, Furumoto conducted a reconnaissance gravity survey over Kaho'olawe which showed that the highest Bouger anomalies were in the southern half of the island (Figure 5.3). Since gravity highs are associated with dike zones and rift zones on other Hawaiian islands (Strange et al.,1965), this is taken as additional confirmation of the rift zones initially identified by Stearns.[4]

No further work regarding ground water (or surface water) on Kaho'olawe was pursued until the Kaho'olawe Water Study, 50 years later. As indicated in the section on geology, in recent years Kaho'olawe has received attention from geoscientists interested in the mechanisms of formation of volcanic islands and in the relation of each island to the formation of other islands (Chen and Frey, 1985; Fodor, et al, 1987). The work of these scientists has confirmed the existence and location of the rift zones on Kaho'olawe, and has provided additional geochemical information that has implications for rock type at depth, consequent weathering products, and the salinity of water contained at depth within the rocks of Kaho'olawe.

Kaho'olawe Water Study: Ground Water Objectives

Using past research as a guide to promising hydrogeologic features on Kaho'olawe, and regional studies of geology and hydrology of ground water in Hawai'i, an investigation of ground water resources on Kaho'olawe was conducted using geophysical tools. Transient electromagentic methods were also used. In addition, shallow ground water monitoring and water quality sampling at

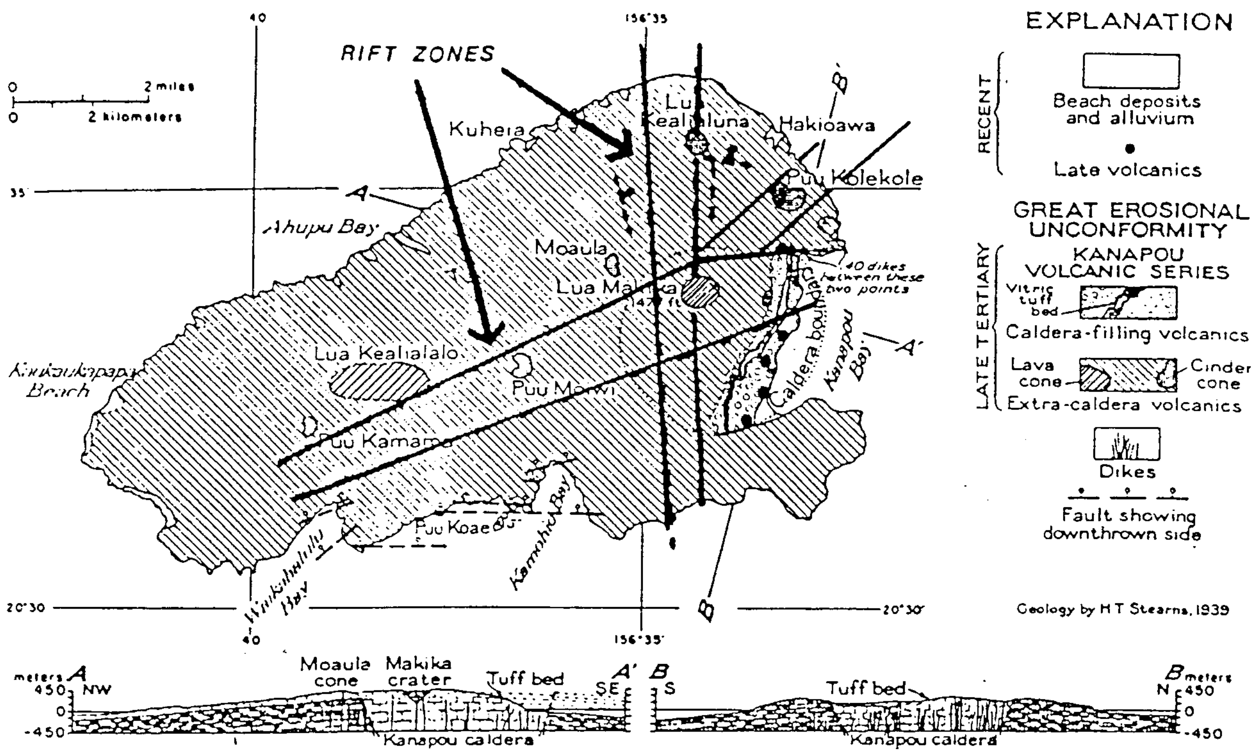


Figure 5.2. Map showing rift zones and associated faulting on Kaho'olawe (Modified from Stearns, 1940, and Fodor, 1988).

Hakioawa Bay was conducted as a means of determining the presence and quality of ground water and the fluctuation of ground water levels in the region.

The objectives of the ground water research were to:

1) Determine the geometry, location and thickness of the ground water resource;
2) Install monitoring devices and determine the effect, if any, of tides on ground water levels at selected localities on Kaho'olawe;
3) Identify a development and management plan for ground water resources on Kaho'olawe.

Preliminary identification of the geometry and thickness of the ground water resource was determined using electromagnetic and Schlumberger soundings. Briefly, the method involves the introduction of an electrical current into the ground and the measurement of the resistivity of earth material to the current. Since certain rocks have a characteristic, or "signature" resistivity, it is possible to interpret the stratigraphy of the earth materials, developing a "geoelectric" section. A goal with regard to the Kaho'olawe study was to find the depth to and thickness of the geologic units which are saturated with fresh water.

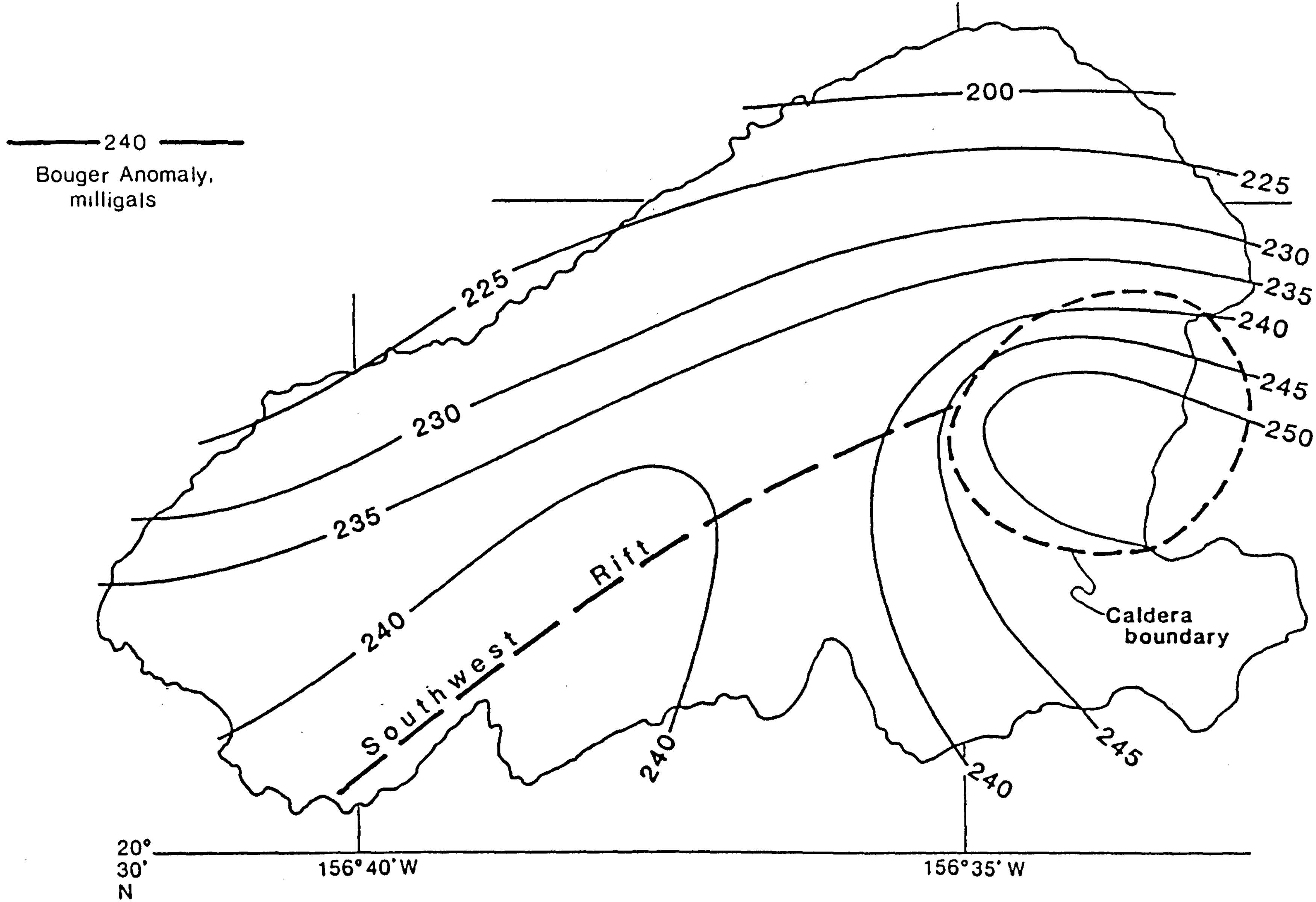


Figure 5.3. Map showing the results of a gravimetric survey of Kaho'olawe conducted by Furumoto in 1965. The figure illustrates a gravity high on the southern portion of the island, a feature often associated with a rift zone.

The determination of the effect of tides on ground water levels was accomplished by installation of a ground water level recorder on the well at Hakioawa Bay. Water quality analyses of ground water at Hakioawa (Takasaki, 1989) reveal its essentially brackish character (2040 milligrams/liter, Total Dissolved Solids) however, the well is recharged and is diluted considerably after rainstorms.[5] The height of the water level at the well above sea level was determined by surveying the site with a transect from the shore to the well (U.S.G.S., 1988). Employing the Ghyben-Herzberg relation, the thickness of the freshwater zone and depth to salt water for the occurrence of a basal lens is calculated.

Hydrogeologic Setting

Rock Types and Permeabilities

The hydrogeologic framework for ground water resource occurrence on Kaho'olawe is in many ways typical of other Hawaiian islands, with certain additional characteristics reflecting the island's development and land use history. As a first consideration, the rock types of Kaho'olawe, discussed in the geology section, are key to the identification of ground water occurrence and movement. Recalling that Stearns divided the island's rock types into three groups: 1) shield- building lavas, 2) ponded caldera-filling lavas, 3) post-caldera lavas and pyroclastic and recent materials (including dikes), there is no doubt that the hydrologic properties of these rocks impact the occurrence, storage and movement of ground water on Kaho'olawe.

The major rock types differ in their grain sizes, weathering potential and form, and a number of factors that affect the distribution of water within the rocks. For example, the pre-caldera volcanics, which range in thickness from 5 to 100 feet, weather with scraggly, rough outcrops as a result of their highly vesicular structure. These lavas transmit water freely, and nearly everywhere on the coasts highly permeable lavas crop out, with sea water moving readily inward and groundwater with an avenue seaward.

Caldera-filling volcanics, on the other hand, exposed in the cliff of Kanapou Bay, are dense and fine grained, with thicknesses approaching 1,000 feet. These rocks extend to an unknown depth beneath Kanapou Bay and probably act to retard sea water intrusion into the rocks of the southwestern rift zone. These rocks are interbedded with lenses of breccia, tuff and talus, all differing in their relative capability to move and store water.

Post-caldera lavas range in composition from olivine basalts to andesites, and are dense, light-gray massive bodies averaging 40 feet in thickness. These rocks crop out north of Lua Makika, at Lua Kealialuna, in Kuhe'eia and Ahupù Bays, at Pu'u

Moiwi and on the southwest side of Pu'u Kolekole, and would yield water only along fractures.[6]

Intrusive rocks, or dikes, cut both pre-caldera and caldera-filling basalts on the entire eastern shore of Kaho'olawe. Dikes are also exposed in Ahupu Gulch, Kuhe'eia gulch and near Lua Kealialuna.[7] The dikes are mostly dense and fine grained, although a few with vesicular sections have been mapped. Over 200 dikes are exposed in Kanapou Bay, on the eastern shore of Kaho'olawe. Dikes would serve to impound or to trap water in compartments between them or within the vesicular portions of dikes. The critical feature appears to be the density and orientation of dikes and their ability to enhance water storage.[8] In addition, Figure 5.4 illustrates the several ways in which dikes serve to enhance the formation and occurrence of springs.

Table 5.1 presents information on the hydrologic properties of similar rocks in the Hawaiian island chain. The wide variety of values for hydrologic properties underscores the change in properties resulting from different modes of extrusion from the volcano and post-extrusive cooling. Figure 5.5 documents the many ways in which secondary permeability may develop within volcanic rocks as they age.

Table 5.1 Hydrologic Properties of Basaltic Rocks of Selected Hawaiian Islands

Rock Type	Porosity	Bulk Density	Hydraulic Conductivity
Bedded Tuffs, partially zeolitized	39-42%	1.5 gm/cm.	73 gal/day/ft
Bedded Tuffs, pumiceous	40-55%	1.37 gm/cm	209 gal/day/ft
Friable Tuffs	36%	1.50 gm/cm	25 gal/day/ft
Pahoehoe Lava Flows	25-50%	------	1000 gal/day/ft
A'a Lava Flows	10-20%	------	.01 gal/day/ft
Dense, fine-grained Dikes	10-15%	------	.001 gal/day/ft

Sources: Meinzer (1942), Davis and DeWeist (1965), Freeze and Cherry (1979), Stearns (1939), MacDonald (1981), Takasaki and Mink (1985).
[Note that soils interbedded with these rock types can increase hydraulic conductivity between units by several orders of magnitude. Also, secondary permeability may develop as a result of the subsequent fracturing or weathering of the rock.]

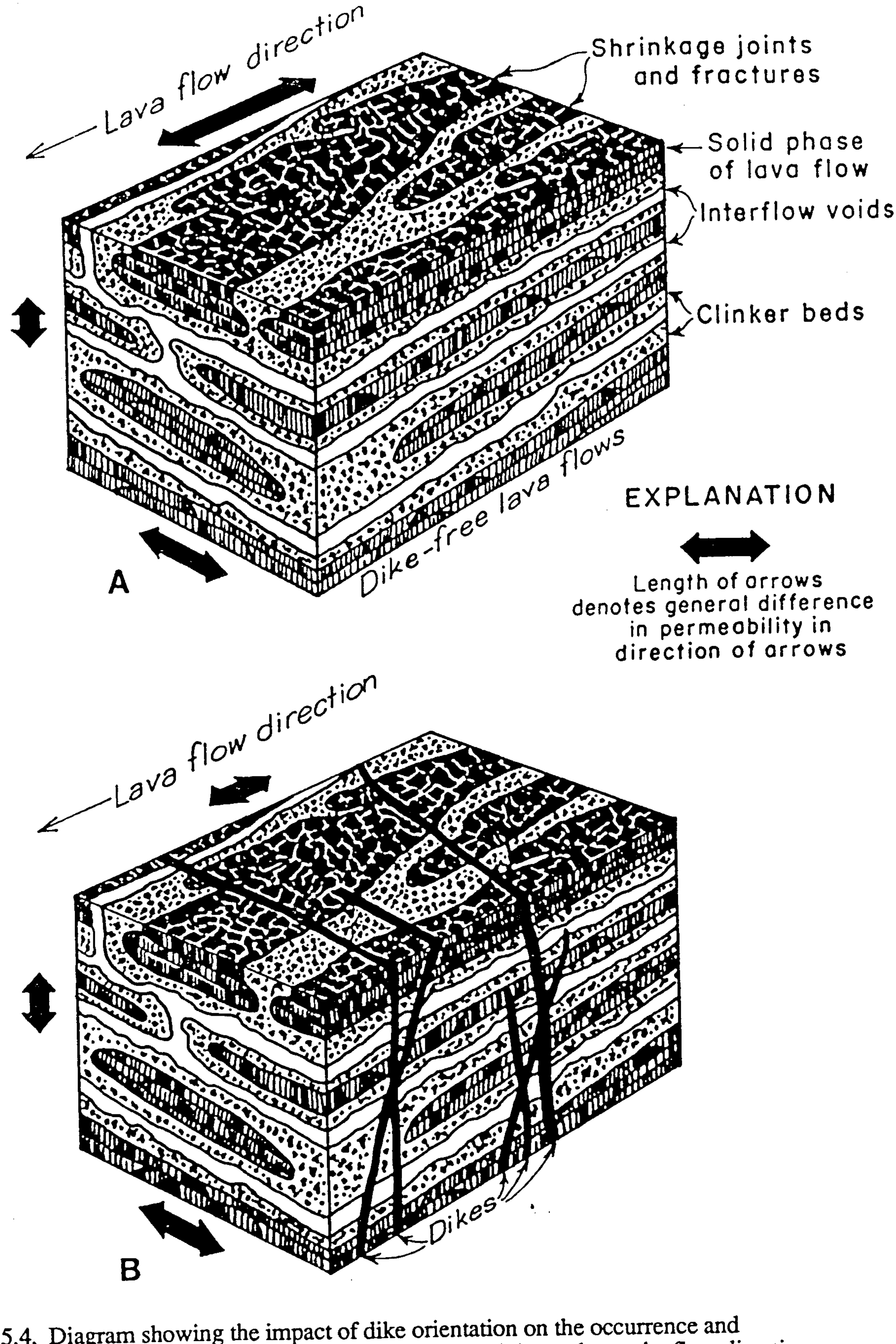
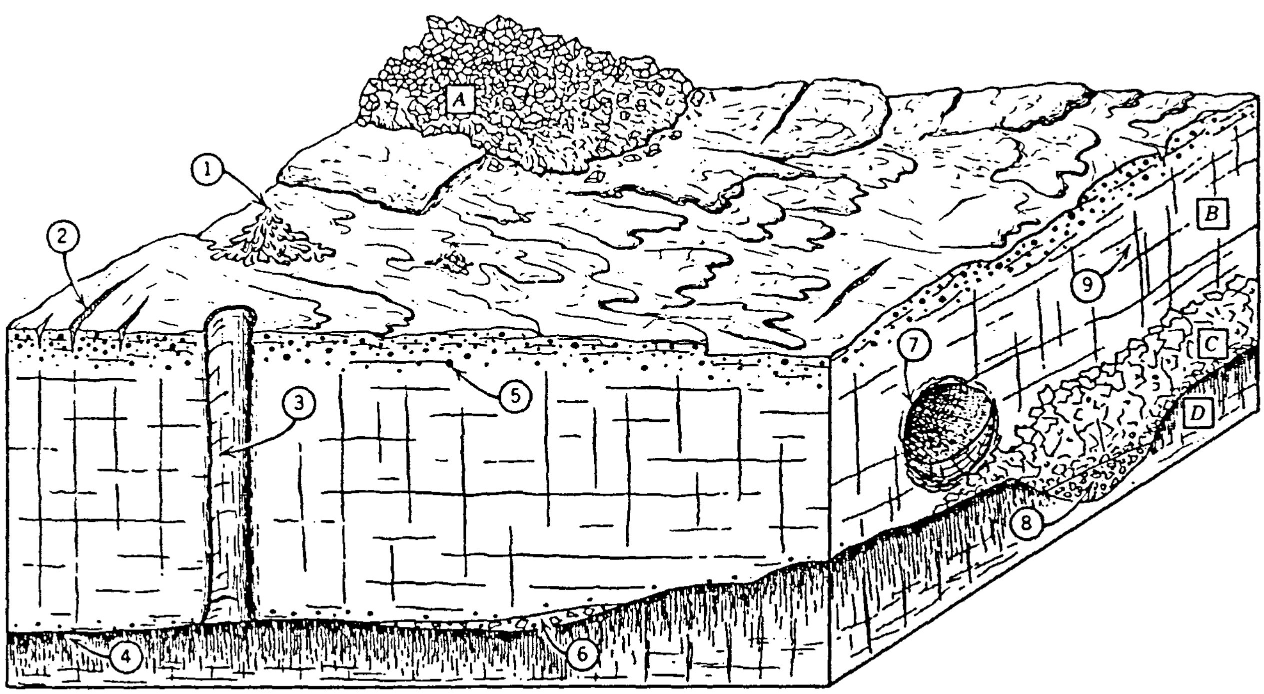


Figure 5.4. Diagram showing the impact of dike orientation on the occurrence and movement of ground water. Where dikes are intruded at right angles to the flow direction, the permeability of rocks is significantly lower (Modified from Takasaki and Mink, 1985).



Features Producing Porosity

① Orifice of spatter cone
② Crack on small pressure ridge
③ Tree mold
④ Buried Soil
⑤ Vesicles
⑥ Small pocket of pyroclastic blocks
⑦ Lava-tube
⑧ Buried stream gravel
⑨ Cooling joint

Sequence of Flows

A. Recent a'a flow
B. Recent pahoehoe flow
C. Ancient buried a'a flow
D. Very old buried pahoehoe flow

Figure 5.5. Diagram showing the development of secondary permeability in volcanic rocks The diagram represents a hypothetical sequence of lava flows showing various features that produce permeability and porosity within basaltic rocks. (Modified from Davis, 1965 and Takasaki and Mink, 1985).

Occurrence and Movement of Ground Water

Figure 5.6 presents a diagrammatic cross section illustrating the occurrence and development of ground water in an idealized volcanic dome. The diagram presents a framework in which it is possible to identify the most likely places for ground water occurrence on Kaho'olawe. Note that the diagram presents ground water occurring as (a) dike-impounded water, (b) a fresh basal ground water lens,
(c) perched water between ash beds and (d) transitional (or brackish) sea water.

As with other shield volcanoes, Kaho'olawe is constructed chiefly of thin lava flows, rapidly poured from their source. Although rapid cooling would imply dense rocks as products, the extent weathering and fracturing could produce secondary impacts which increase permeability. Ash beds, which are prevalent on Kaho'olawe, are interbedded with these pahoehoe and 'a'a lava flows. Hence, perched water develops along both ash beds and lava flows. When recharge is plentiful, seeps occur long after rain falls; as Stearns noted in 1939, springs were observed and measured in a cliff on Kanapou Bay and emanated from a fracture between two thin lava flows.

In addition, basal ground water lens can develop and may accumulate over centuries as precipitation infiltrates the land surface or beds of stream channels. The lens may be thick or thin depending on a host of factors; it is clear that the basal lens can also be depleted by well development, extensive vegetation growth, or reduction in freshwater recharge. A typical basal lens is indicated in Figure 5.7.

As discussed in the geology section, Kaho'olawe consists of three major rift zones, which are shown in Figure 5.2 Although the rifts were buried by later lava flows, which may in fact be fine grained, the scarps along which the rifts initially collapsed continue to form avenues where recharge could find its way to the subsurface. Moreover, because evidence of numerous dikes in each major extension of the rift zone, it is likely that dikes penetrate the entire rift zone complex. Compartmentalization of water by dikes in the manner shown in Figure 5.4 is therefore possible for Kaho'olawe. A significant feature in this regard is that the dikes, as observed by several researchers, are fine grained and dense materials. It is also likely that the number of dikes increases with depth in the island.[9] The increasing number of fine-grained dense dikes with depth would also serve to insulate compartmentalized fresh water from sea water encroachment (Stearns, 1939; Meinzer, 1953; Todd, 1985).

Finally, fracturing accompanying rifting, emplacement of dikes, large-scale normal faulting on the southern and eastern sides of Kaho'olawe, and a pattern of radial fracturing emanating from Lua Makika act to open local avenues for subsurface movement of water. It is likely that several stream courses follow the course of faults associated with the formation and development of Kaho'olawe and these streams may act to funnel recharge to the subsurface, however meager. As more information becomes available for surface water discharge, analyses of

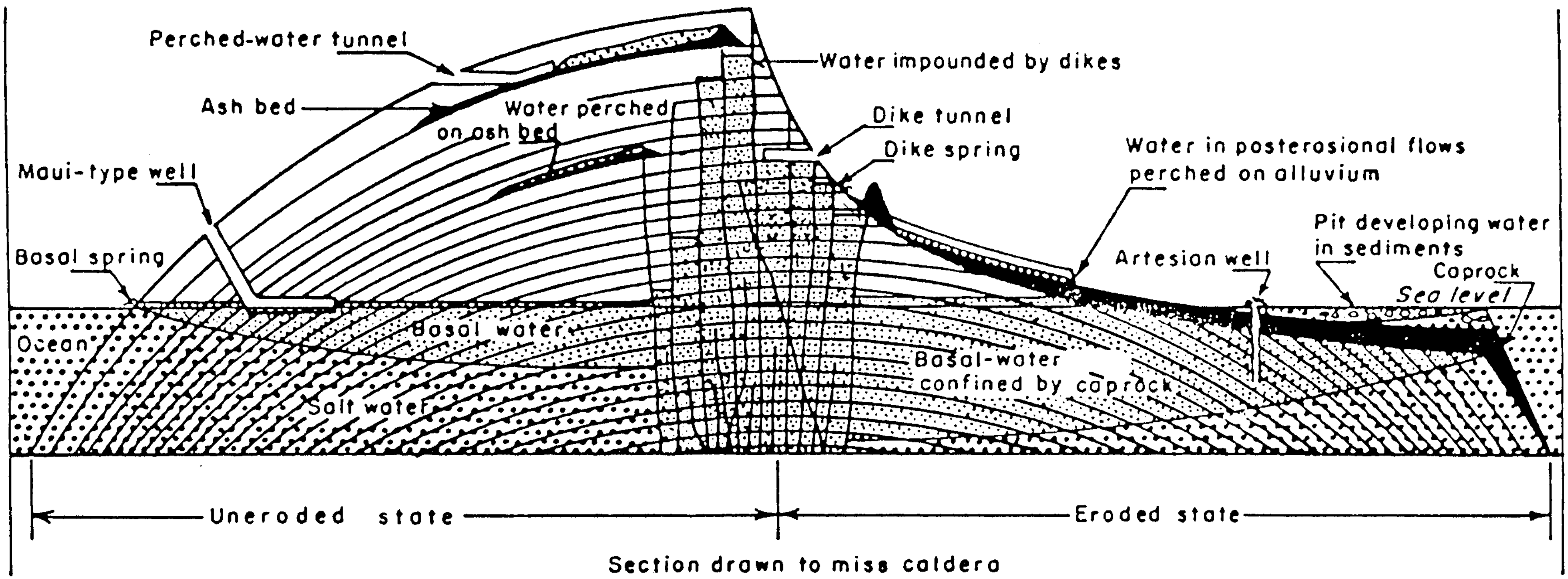


Figure 5.6. Occurrence of ground water in an idealized volcanic dome (After Macdonald, 1983 and Todd, 1982).

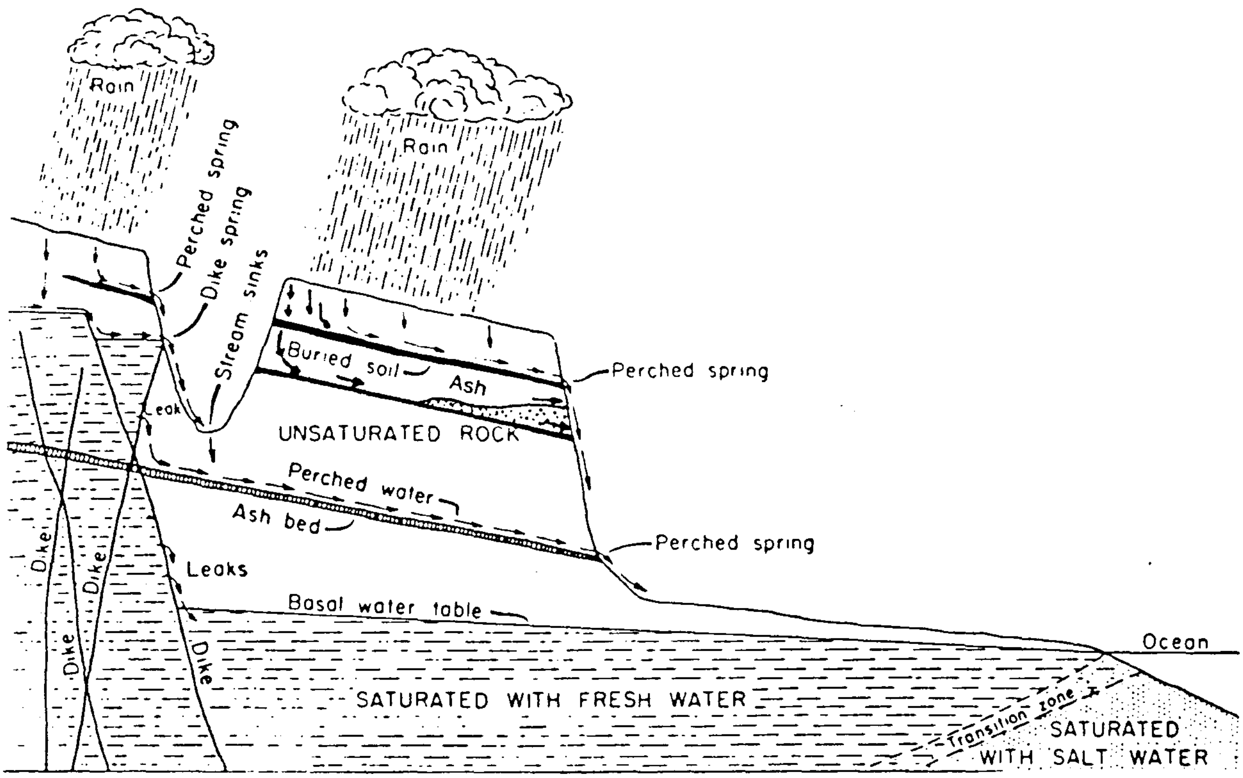


Figure 5.7. Diagram showing the typical occurrence of a basal ground water lens (Modified from Macdonald, 1983).

hydrographs and water balance information can reveal this component of seepage into Kaho'olawe's channels.[10]

Without a series of wells in which to measure water levels and gradients, and without a series of springs to measure discharge, it is impossible to determine accurately the presence of ground water and the direction and rate of ground water movement. It is only possible to speculate on the probable environments of ground water occurrence and to link field observations of springs and seeps to this likely environment.

Geophysical Investigations for Ground Water

Given the foregoing background analysis of the potential occurrence of ground water on Kaho'olawe, a geophysical investigation was designed and conducted by the U.S. Geological Survey in selected portions of the island deemed most likely to contain ground water. A total of five Schlumberger and 24 transient electromagnetic soundings were conducted on Kaho'olawe during March and September 1988 and in January 1989.

Methodology

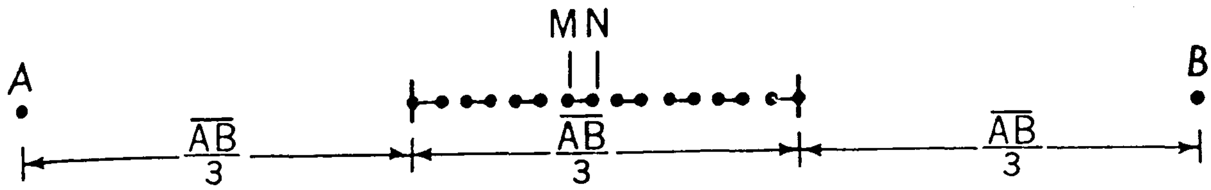
Although a complete discussion of the techniques of electrical resistivity surveys is beyond the scope of this document, it is helpful to review the principles so that results discussed in the conclusion can be grasped and interpretations drawn.

In making resistivity surveys, a commutated direct current or very low frequency current (<1 Hz) is introduced into the ground via two electrodes ("current electrodes"). The electric potential difference is measured between a second pair of electrodes ("potential electrodes"). The electrical resistivity of the rock material will control the gradient of electric potential created when the current is introduced into the ground. If the four electrodes are arranged in any of several possible patterns, the current and potential measurements may be used to calculate the resistivity of the rock material. The depth of penetration of the current is controlled by the spacing of the current electrodes; the farther apart, the deeper the penetration. At each electrode set-up, an apparent resistivity is calculated on the basis of the measured potential drop, the applied current and the electrode spacing (Dobrin, 1976).

An example of the Schlumberger electrode array is presented as Figure 5.8. The apparent resistivity at the center of a Schlumberger array is:

$$\rho = \pi \frac{(\overline{AB}/2)^2 - (\overline{MN}/2)^2}{\overline{MN}} \frac{\Delta V}{I}$$

Apparent resistivities, as measured in ohm-meters, are plotted as a function of electrode spacing on semi-log coordinate paper, with the curve of the apparent resistivity called the electrical resistivity sounding curve. An example resistivity sounding curve for a locality on O'ahu is presented in Figure 5.9.



where: MN = length of "potential" line
AB = length of the "current" line

Figure 5.8. Diagram illustrating the arrangement of electrodes in a typical Schlumberger electrical resistivity survey (Modified from Dobrin, 1965).

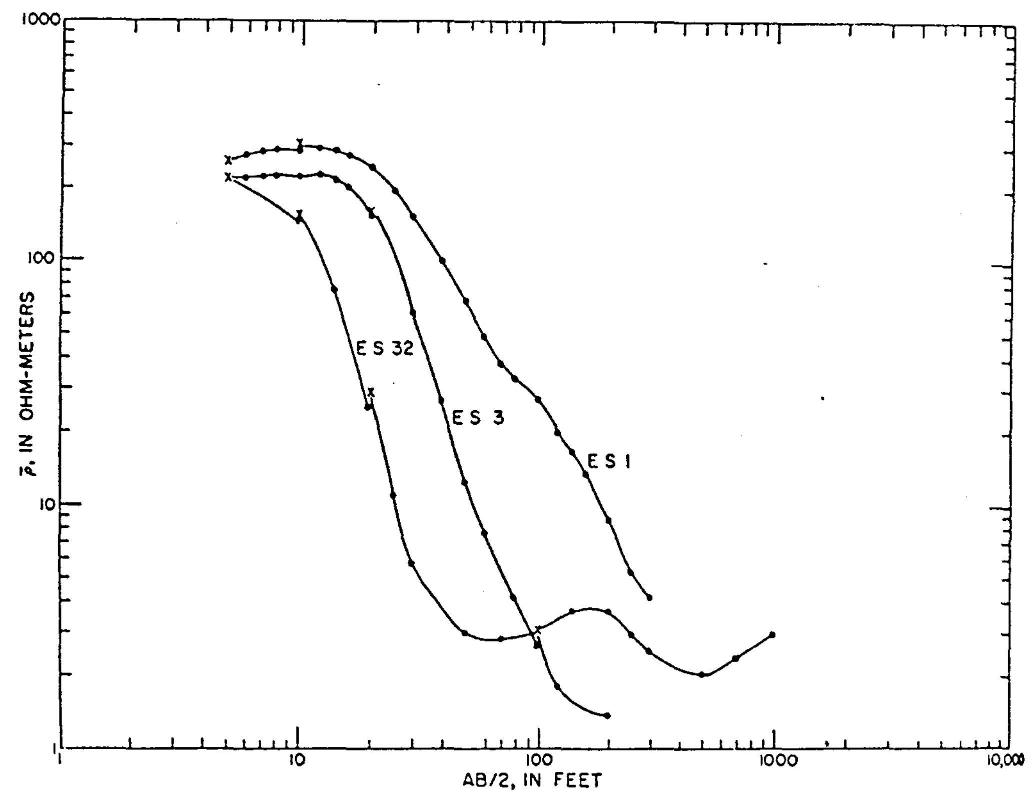


Figure 5.9. Diagram illustrating an electrical resistivity curve for O'ahu (Zhody et al, 1980).

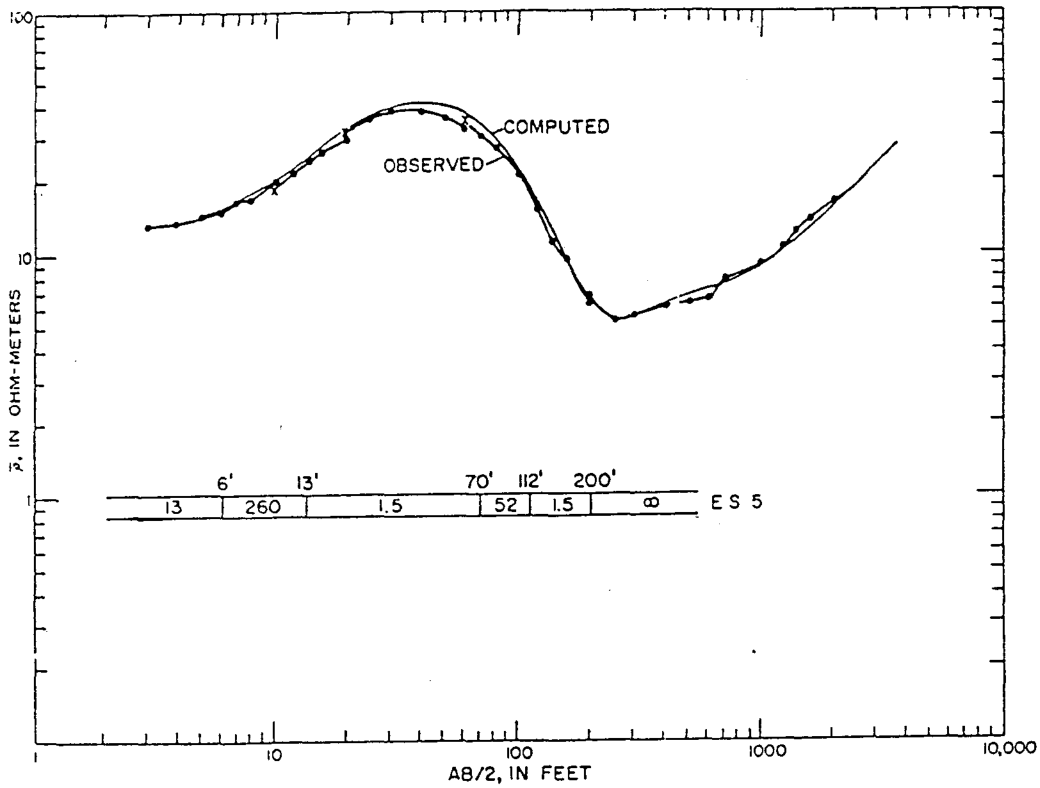
As the spacing between electrodes is increased, the change in apparent resistivity with electrode spacing determines the variation of resistivity with depth. Rock types may then be identified by this process. Table 5.2 presents selected resistivity values for rock types and sediments in Hawai'i, illustrating the wide variation in electrical resistivities as well as "characteristic" values for selected Hawaiian conditions (e.g., sea water saturated basalts). The numeric value of apparent resistivity is a function of the electrode spacing, the geometry of the electrode array, and characteristics of the subsurface, such as the layer thickness, angles of dip, anisotropic properties and other factors.[11]

Table 5.2 Electrical Resistivity Values for Selected Rock Types and Sediments, Hawai'i

Rock or Sediment Type	Electrical Resistivity Ohm-meters	Source
Fresh Basalt saturated with sea water	30-40	1
Fresh basalt saturated with fresh water	300-700	1
Weathered basalt saturated with freshwater	30-60	1
Basalt saturated with sea water	< 30	1,3
Gravel and sand, saturated with fresh water	100-200	2
Limestone	1;000	2
Clay saturated with brackish to saline water	< 3	1,2
Clay saturated with fresh water	5-8	2
Sand and Coral	40-400	2
Clay, silty sand and some gravel saturated with fresh water	11-20	2
Fresh Water	50	1
Brine	.005	1

Sources: Zhody et al, 1980; Davis and DeWeist, 1965; Kauahikaua, 1988

Considering the wide range in possible sequences subsurface of geologic materials in the construction and development of an island, stratigraphic interpretation is possible from examination of sounding curves only within the limits of precision that depend on the subsurface layering configuration. To aid in the interpretation of complex electrical sounding curves obtained from the field, a comparison of field curves with theoretical curves generated from readily-available multi-layered models is undertaken (Zhody and Jackson, 1969; Zhody et.al.,1974; Kauahikaua, 1988). An example is shown in Figure 5.10.



ES 5 curve. Theoretical curve calculated by computer. Interpretation indicates: Top soil (13 ohm-m), first coral (260 ohm-m), second coral (52 ohm-m), clay (1 ohm-m), basalt (very high resistivity in relation to overlying clay layer).

Figure 5.10. Diagram comparing a field resistivity curve with theoretical curves generated from multi-layer models of subsurface resistivity (After Zhody, 1981).

In the transient electromagnetic method, a time varying electromagnetic field in the frequency range between 100 and 5,000 Hz passes through a wire loop, inducing a magnetic field. A second wire loop is also used. When this primary magnetic field is imposed on the rock materials, a flow of electrical current results. The amount of current flow, as in other electrical surveys, depends on the conductivity of the layers (Zhody and Jackson, 1969).

This current then produces a secondary magnetic field which has the same frequency as the primary field, but not the same phase or direction. The secondary magnetic field is then detected by measuring the voltage induced in the second loop of wire (the receiving loop) by the magnetic current. In this method, the effective depth at which conductive bodies can be detected is dependent upon both the frequency and spacing between the transmitting and receiving loops. As with the electrical resistivity method, interpretation is accomplished by curve matching or modeling.

Field Procedures and Results

During August and September 1988 and January 1989, the U.S. Geological Survey conducted a geophysical survey of Kaho'olawe using Schlumberger and transient electromagnetic techniques described above. Figure 5.11 presents the location and type of soundings conducted during the course of work. The map demonstrates the island-wide geophysical coverage of Kaho'olawe that now exists as a result of this study, and represents the most current interpretation of ground water possibilities for the island.

The soundings were intended to determine the depth to the conductor at or below sea level, thought to represent sea water saturated basalt. Additional information on the vertical structure of the island was also derived from the soundings.

Electrical resistivity data for Kaho'olawe is shown in Table 5.3. Significantly, both types of soundings reveal that the general structure of Kaho'olawe is made up of three zones. The surface zone, representing the first 265 feet below the land surface, consists of one or two layers of low resistivity (8-30 ohm-meters), with the surface layer roughly twice as resistive as the lower layer. This is interpreted as weathered basalt (post caldera), with low resistivities attributed to in-situ development of secondary clay minerals. It is likely that small quantities of saline water are present. The thickest portion of the weathered zone is beneath Lua Makika.

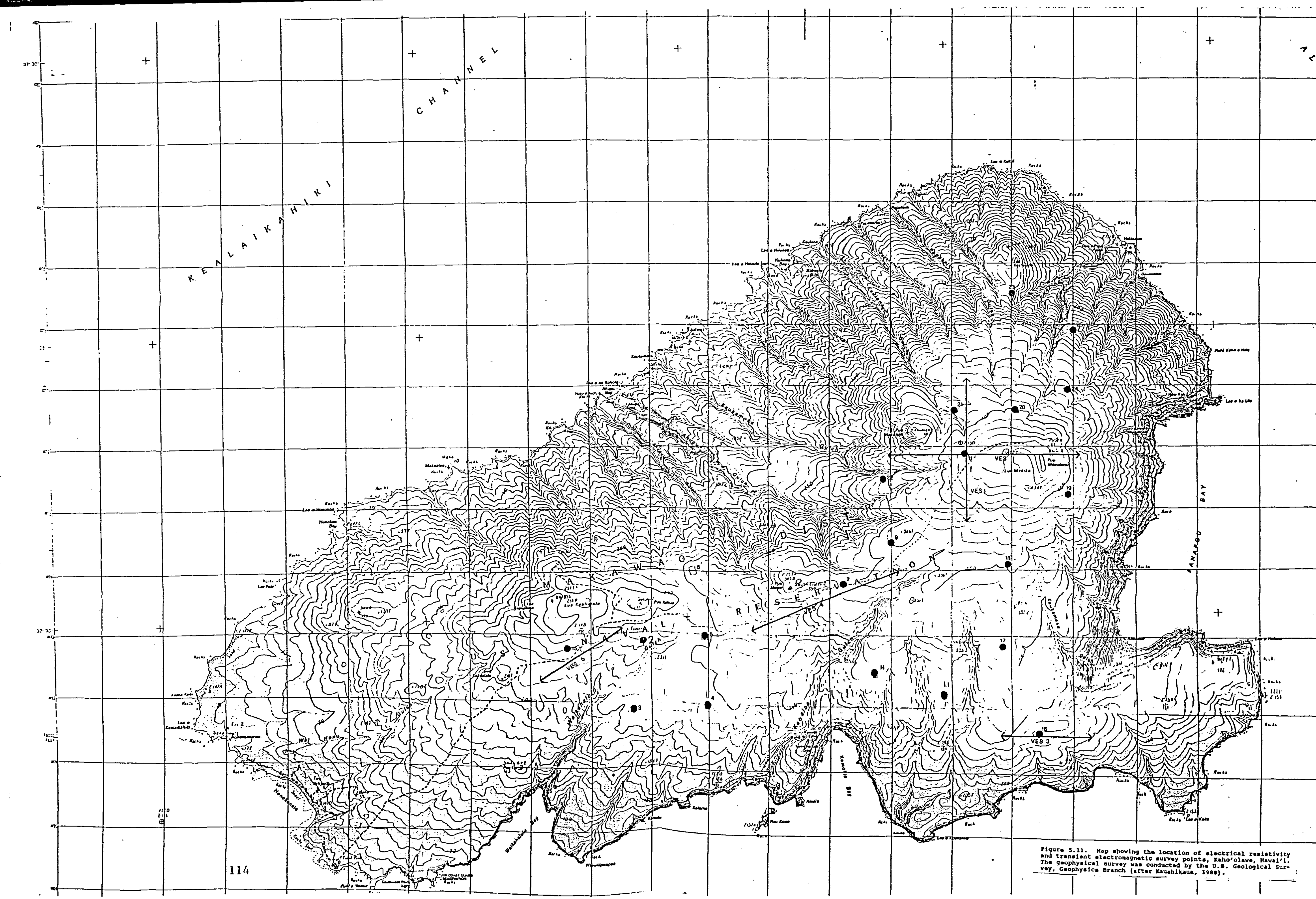


Figure 5.11. Map showing the location of electrical resistivity and transient electromagnetic survey points, Kaho'olawe, Hawai'i. The geophysical survey was conducted by the U.S. Geological Survey, Geophysics Branch (after Kauahikaua, 1988).

Table 5.3 Electrical Resistivity Data for Kaho'olawe

Sounding Location (see Fig 5.11)	Elevation (meters)	Weathered Zone (meters)	Basalt Resistivity (ohm-meters)	Salt Water Saturation Zone (ohm-meters)
1	295	11.1	997	4.4
5	240	9.8	727	4.7
10	400	10.4	154	2.4
17	310	13.3	177	5.3

Source: Kauahikaua, 1988.
[Note: These are selected values only. There were over 25 soundings conducted on Kaho'olawe between March 1988 and January 1989.]

The second zone has the highest resistivities (greater than 38 ohmm) and extends the section another 400 feet below the surface. The values are interpreted as representing unsaturated, unweathered basalts (Kauahikaua, 1988). However, Zhody's resistivity values of 60 ohm-m for O'ahu include weathered basalts saturated with fresh water. Weathering, through the production of clays, could again affect the resistivity readings. Certainly the lower layer of this zone would be less weathered and have characteristically higher resistivities (> 100 ohm-m). The lowest resistivity values in this zone, around 50 ohm-m, occur beneath Lua Makika.

Significantly, Kauahikaua reports that in comparison with electrical resistivity values for unsaturated, unweathered basalts obtained from other Hawaiian islands, the values for Kaho'olawe are low. Alteration of basalts to clay minerals, principally montmorillonite, would again act to lower resistivities. Hydrothermal fluids known to exist within Kaho'olawe and trapped as fluid inclusions within these rocks at depth would also lower electrical resistivity readings (Fodor et al., 1987).

The third, and deepest zone, has low resistivities (<40 ohm-m), with some regions of this zone exhibiting two layers of both low and intermediate resistivities (9-60 ohm-m). The layers whose resistivities are 4 ohm-m and lower are interpreted to represent sea-water saturated basalts.

From the foregoing, it is apparent that a zone of fresh water exists beneath the eastern and southern portions of Kaho'olawe (Takasaki, 1989 and Kauahikaua, 1989). Figure 5.12 presents a map of the apparent freshwater lens thickness, calculated as the difference between the elevation of the zone with resistivity values of 5 ohm-m or less and the surface elevation (Kauahikaua, 1988). As can be seen from the figure, the ground water feature is narrow and confined to a certain portion of the island. The ground water zone correlates well with the south-west and north-south rift zones. The thickest part of the feature is beneath Lua Makika, with an abrupt northern boundary and diminishing to the west and southwest. No information is available at this point as to the eastern boundary of the feature.

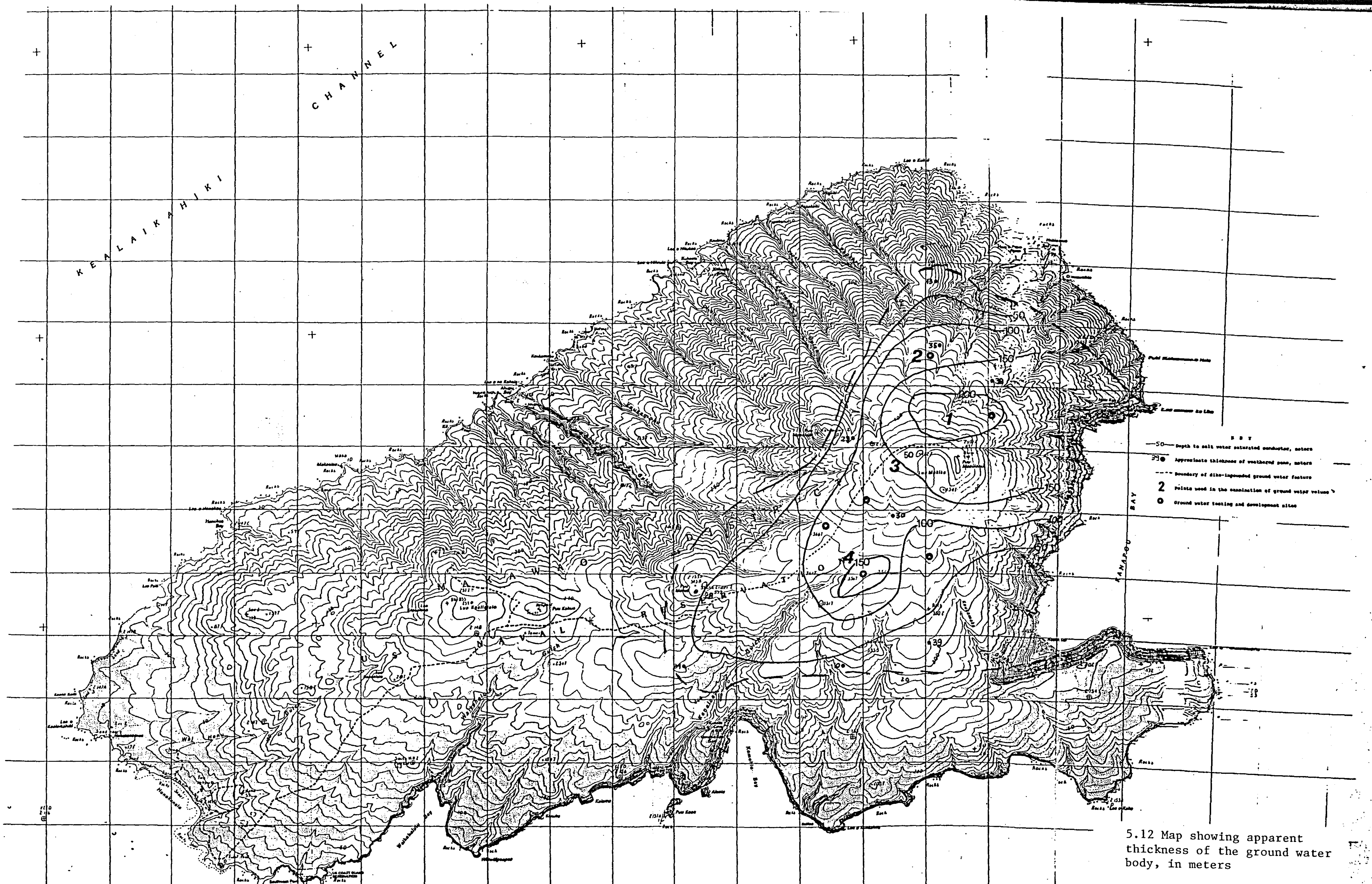
The ground water feature covers an area of approximately 15,000 acres and is an average 300 feet in thickness. Figure 5.13 presents a schematic diagram illustrating the current interpretations of the geophysical survey.

Discussion

The discovery of both dike-impounded and basal ground water on Kaho'olawe is not surprising, given the many possible structural features which would encourage even minor entrapment of water. However, several precautions must be taken in interpretation of results, which is one of the reasons why Figure 5.12 presents the contours of <u>apparent</u> lens thickness. First, interferences with electrical resistivity and transient electromagnetic readings, such as superparamagnetic soil material (Buselli, 1982), buried metallic ordnance, and effects of communications wires on the land surface must be factored into interpretations of layer resistivities. Secondly, the production of clay minerals in the subsurface, which is an inevitable consequence of the breakdown of basaltic rocks, may significantly lower resistivities, giving false indicators of fresh water or salt water saturated materials. Finally, long-entrapped hydrothermal fluids, suspected of producing a unique mineral assemblage on Kaho'olawe, may be responsible for anomalously low resistivities in unweathered basalt at considerable depth on Kaho'olawe.

The ground water feature identified has well defined boundaries that are coincident with the rift zones known to exist on the island. Electrical resistivity measurements on the northern half of the island and water quality and water level measurements in the northeastern half of the island do not indicate the presence of a thick basal lens on the island's periphery. These two facts, coupled with the field identification of hundreds of dikes on Kaho'olawe suggest that the ground water feature is dike-impounded ground water, compartmentalized within the ancient rift zones of the island.

On the balance, Kaho'olawe has throughout most of its history been a semi-arid island, with little annual rainfall. The high freshwater head on Kaho'olawe, in light of low annual rainfall, is unusual. This would suggest that the ground water feature is contained within very fine-grained, or low permeability units, which may indicate low ground water yield. However, as indicated by the experience on other islands, the penetration of a dike compartment often yields high quantities of water, at least initially (Stearns, 1940). With low average rainfall on Kaho'olawe, and thus limited recharge, a major question is whether dike compartments, when penetrated, could sustain yield over the long term. The definition of "low yield" is important as well. In light of the water needs of critically-needed vegetation on the



5.12 Map showing apparent thickness of the ground water body, in meters

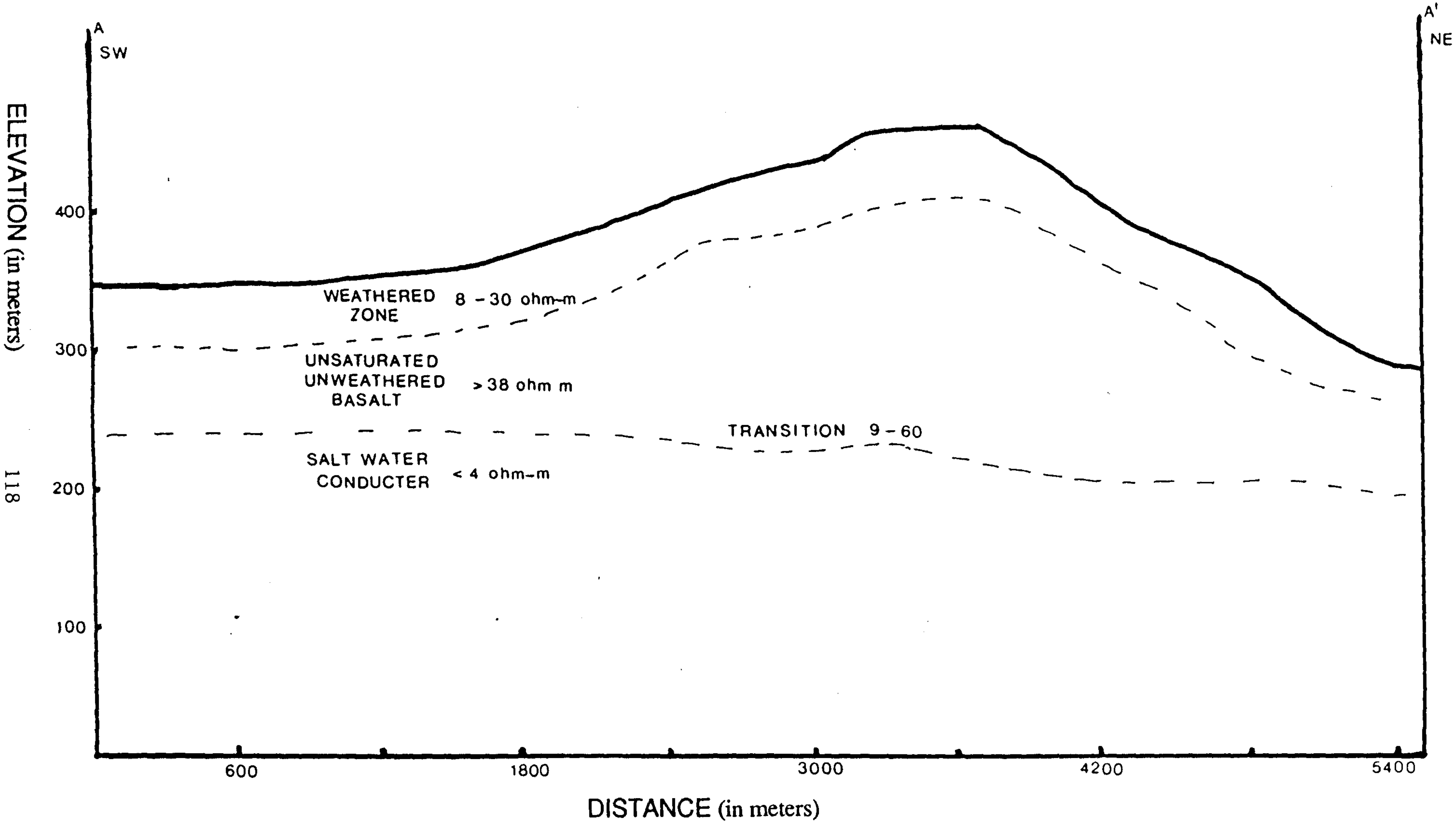


Figure 5.13. Schematic diagram showing an interpretation of the geophysical data collected and analyzed by Kauahikaua (1988). See Figure 5.12 for the location of the cross section. The dikes that impound this ground water feature are not shown in the diagram because of the lack of information on dike orientation, strike and dip. Note that the unsaturated, unweathered zone may in fact contain water; electrical resistivity values for this zone are anomalously low.

hardpan area (under which lies the ground water resource), even 20 gallons per minute with storage facilities could provide a significant quantity of water.

An unknown quantity is the quality of ground water. In view of generally low resistivities encountered in the survey, the rock types present and their weathering products, and the possible presence of relict hydrothermal fluids, it is likely that ground water may contain high dissolved solids; ground water may actually be quite saline in many areas simply as a result of in situ geochemical processes.

The next stage in the investigation of ground water resources on Kaho'olawe, in view of the remaining unanswered questions regarding yield and quality, is a comprehensive drilling and testing program. Clearly the large investment of time and dollars required to deliver a drilling rig to Kaho'olawe make the development of a comprehensive and effective investigation a prerequisite to final well development and initiation of use.

Water Quality and Water Level Measurements

In 1939, an electrical resistivity survey reported the existence of a thin basal ground water lens standing approximately 1 to 1.5 feet above sea level in the Ahupu Gulch area. To provide additional insight into and confirmation of a basal lense, water level measurements in a well at the mouth of Hakioawa Gulch were conducted as a portion of the Kaho'olawe Study. Information regarding the occurrence, quality, and recharge of ground water was obtained.

The water level in the well at Hakioawa stands approximately .17 feet above sea level, as measured by the U.S. Geological Survey in October, 1988. A sample taken in October 1988 and reproduced in Table 5.4 illustrates the well's brackish water quality; however, subsequent rainstorms recharged the well and water quality improved markedly. Chloride concentrations dropped from 16,000 mg/l to 1100 mg/l from October to January.

Employing the Gyhben-Herzberg relation, which states that for every 1 meter of fresh water that lies above sea level, 40 meters of fresh water extend below sea level, the apparent thickness of the ground water lens is 10 feet.[12]

Because of the well's proximity to the coastline, it was theorized that the ground water level would exhibit fluctuations as a result of tidal influences. However, the hydrograph (October 1988-January 1989) exhibits little, if any, change or response to tidal influence. The hydrograph does show the recharge of the well as a result of rainfall occurring during the study period. The rain gage record and the well hydrograph mirror the sudden bursts of rainfall characteristic of Kaho'olawe rains (Figure 5.14). The hydrograph also reveals the steady decline of the water level after rainfall events suggesting the well loses water. The water level

Table 5.4. Ground Water Quality Analyses, Hakioawa Well, Kaho'olawe.
[Sample and analyses by the U.S. Geological Survey, 1989]

Date of Sample	Oct 20 1988	Oct 28 1988	Jan 17 1989
Time Sample Taken	1235	1120	1425
Record Number	98900148	98900147	98900145
Temperature of Water (Degrees Celcius)	---	---	23.0
PH Lab (Standard Units)	---	---	7.50
Residue Total at 105 Degrees Celcius, Suspended (mg/l)	---	---	2
Nitrogen NO_2+NO_3 Dissolved (mg/l)	---	---	0.340
Hardness Total (mg/l as $CaCO_3$)	---	---	510
Calcium dissloved (mg/l as Ca)	---	---	69
Magnesium, dissloved (mg/l as Mg)	---	---	82
Sodium dissolved (mg/l as Na)	---	---	550
Sodium Adsorption Ratio	---	---	11
Sodium Percent	---	---	68
Potassium, dissolved (mg/l as K)	---	---	32
Chloride, dissolved (mg/l as Cl)	16,000	16,000	1100
Sulfate, dissolved (mg/l as SO_4)	---	---	100
Fluoride, dissolved (mg/l as F)	---	---	0.20
Silica, dissolved (mg/l as SiO_2)	---	---	14
Iron, dissolved (ug/l as Fe)	---	---	40
Manganese, dissolved (ug/l as Mn)	---	---	700
Solids, Sum of Constituents, dissolved (mg/l)	---	---	2040
Alkalinity Lab (mg/l as $CaCO_3$)	---	---	146

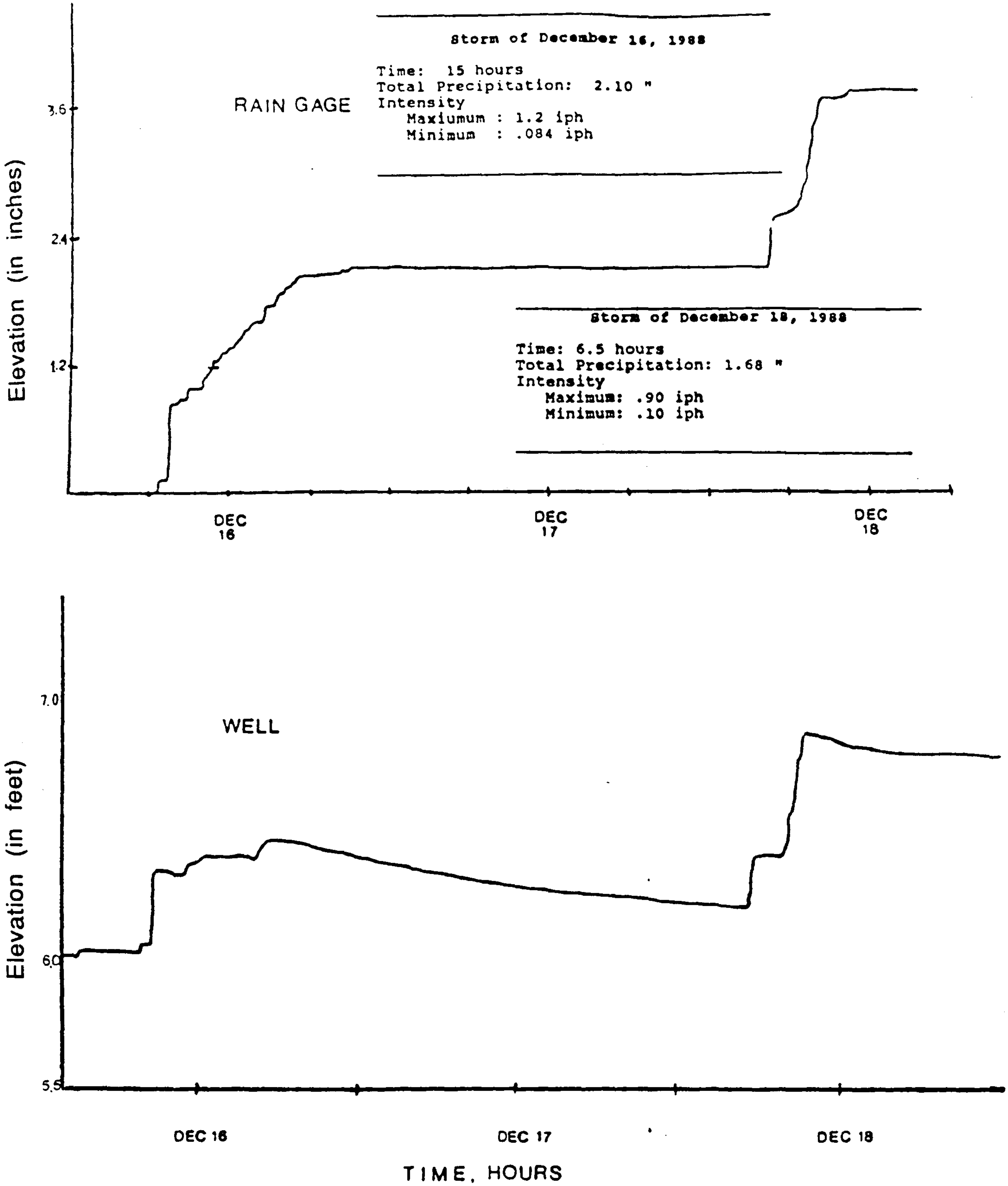


Figure 5.14. Comparison of rain gage and ground water level hydrographs, Hakioawa Gulch, Kaho'olawe. Note the recharge of the well by rainfall.

on January 10, 1989 was substantively the same as when the recorder was installed in October, 1988 despite the fact that recharge had increased the water level over 2.5 feet between that period.

The lack of recharge to the well other than rainfall may suggest that the well is clogged to additional recharge. This is a clear possibility in that the erosion of the hardpan area has deposited large quantities of silt in the alluvial valleys at the mouths of the gulches. In addition, the lack of surface recharge as a result of the increase in surface runoff would affect the quantity of water moving as perched or spring water to recharge the basal lens. The smooth recession of the hydrograph after rainfall events additionally indicates that there is steady demand of water from the well as a result of surrounding *kiawe* trees.[13] The *kiawe* trees are salt-tolerant and can take advantage of brackish water. Ironically, the removal of salt at the root zone of the *kiawe* trees, while protecting the plant, increasingly seals the subsurface to water movement as a result of the interaction of salt with the clays brought down from the erosion of the hardpan. The decline in the hydrograph to original water level takes about 5 days (Figure 5.15).

Ground Water Recharge

For Kaho'olawe, the major recharge zones are located within the caldera of Lua Makika and within small depressions that cap the five cinder cones on island. In addition, recharge occurs along certain porous stream channel bottoms and through direct deep percolation of water through soil zones. Finally, recharge occurs through the faults and fractures bordering and accompanying the rift zones on the island. As mentioned in earlier sections of this report, recharge on Kaho'olawe in the past must have been greater, owing to the thicker soils and the existence of a solid vegetation cover.

As part of the water balance calculations discussed in previous sections of this report, the amount of potential recharge to Kaho'olawe's ground water supply was estimated by determining the area of the potential recharge zones and estimating the quantity of water that could potentially infiltrate in each of these areas to become part of the ground water resource. These data are included as Table 5.5. Again, these values should be considered estimates of potential recharge, with further work desirable.

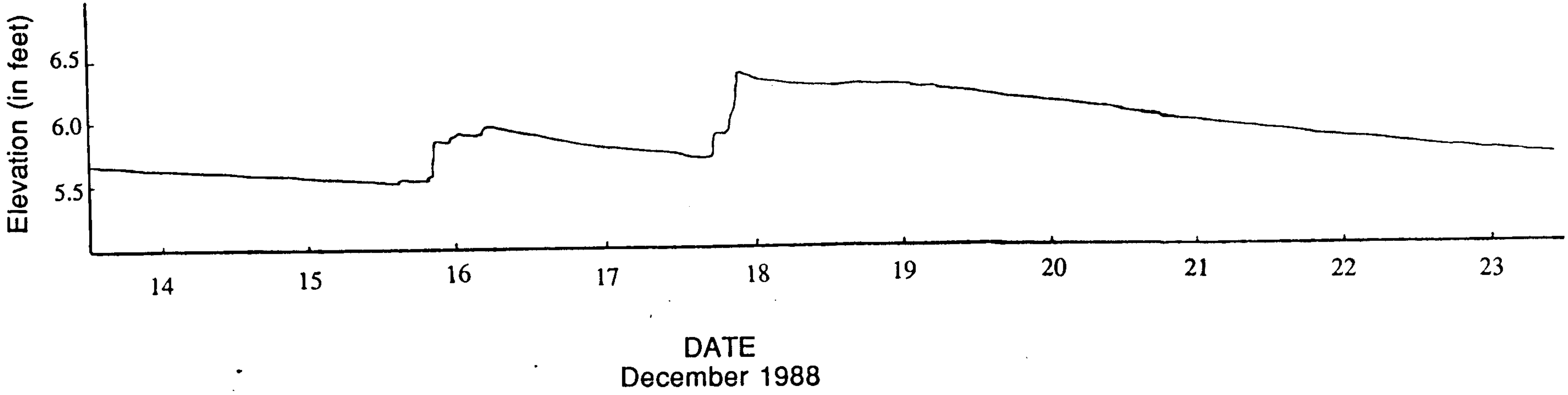


Figure 5.15. Ground water hydrograph of the well at Hakioawa Gulch showing steady decline of the water level in the well over a period of approximately 5 days. The smooth decline is attributed both to seepage from the well and to evapotranspiration demand by surrounding kiawe trees.

Table 5.5. Estimated Recharge Quantities Through Probable Recharge Zone, Kaho'olawe

Recharge Zone [1]	Area (acres)	Potential Recharge (in acre-feet) [2] Amount of Rainfall 25 in	15 in	10 in	Percent of Water Balance[3]
Lua Makika	131	272	164	109	
Lua Kealiluna	27	56	34	23	
Pu'u Moiwi	23	48	29	19	
Moa'ula	23	48	29	19	
Lua Kealialalo	12	25	15	10	
Stream Channels	6	4	3	2	
Bare Soil Surface[4]	6	4	3	2	
TOTALS[5]	**222**	**453**	**274**	**182**	5%

Note: 1 acre foot = 325,900 gallons.

[1] The percent of the annual water balance is computed by determining the quantity of recharge and dividing by the total quantity of rainfall on the island for that year, and is expressed as a percentage.

[2] Only selected stream channels, where the likelihood of faulting is great, were analyzed.

[3] The quantities under "Potential Recharge, 25, 15, 10" reflect different years in which the average annual rainfall is normal or slightly below normal.

[4] These calculations were impossible to compute for individual storms.

[5] Evapotranspiration (ET) loss not calculated for these values. ET may however limit recharge for many of the recharge zones that have trees and other vegetation.

Summary

This chapter has presented the results of ground water research conducted as part of the Kaho'olawe Water Resources Study. Project instrumentation and a geophysical survey conducted by the U.S. Geological Survey revealed the existence of both dike-impounded water and a thin basal lens (although brackish) on Kaho'olawe. A series of possible values for the hydrologic properties of the rocks of Kaho'olawe, given pertinent regional research, was compiled and presented.

After prolonged rainfall on Kaho'olawe, seeps and damp areas can be found emerging between thinly-bedded lava flows on the island. The clay-dominated soils hold moisture and remain slick long after rainstorms.

Notes to Chapter 5

[1] H. T. Stearns, Geology and Ground Water Resources of the Islands of Lanai and Kahoolawe, Hawaii, 1940; G. A. Macdonald, A. T. Abbott and F. L. Peterson, Volcanoes in the Sea: The Geology of Hawai'i, 1968; R. S. Fiske and E. D. Jackson, "Orientation and Growth of Hawaiian Volcanic Rifts: The Effects of Regional Structure and Gravitational Stresses", 1972; K. J. Takasaki and J. F. Mink, Evaluation of Major Dike-Impounded Ground Water Reservoirs, Island of Oahu, 1985.

[2]C.K. Wentworth,"Storage Consequences of the Ghyben-Herzberg Theory" 1942.

[3] Information from Stearns in H. T. Stearns, Geology and Ground Water Resources of the Islands of Lana'i and Kaho'olawe, Hawai'i, 1940, p. 131-132.

[4]A gravity survey is a geophysical technique used to identify different rock types below the land surface by measuring the gravitational attraction of rocks of different density. Density is the key parameter that causes variations in gravitational attraction. A Bouger anomaly is a value that corrects the observed gravity for latitude and elevation variations as well as corrections due to the mass of material above sea level within the earth and topography.

[5]Personal Communication with K.J. Takasaki, 1989. See later sections of this chapter regarding ground water quality.

[6]This depends on the relative amount of weathering of the rocks which, according to J. Kauahikaua, "Preliminary Report on Geophysical Survey of Kaho'olawe, Hawai'i," 1988, may be significant.

[7]Field notes and photographs taken by Dr. C. Vandemoer, Kaho'olawe Water Study, September 1988.

[8]K.J. Takasaki and J.F. Mink, Evaluation of Major Dike-Impounded Ground Water Reservoirs, Island of Oahu, 1985.

[9]Personal communication, K. Takasaki with C. Vandemoer, January 1989.

[10]The pattern of ground water flow would be very difficult to determine in dikeimpounded aquifers.

[11]A. A. Zhody and D. B. Jackson, "Application of Deep Electrical Soundings for Groundwater Exploration in Hawaii", 1969.

[12]If the well draws water from the basalt, instead of the alluvial material, the Ghyben-Herzberg relation would not apply entirely.

[13]Field investigations by 'Ohana personnel during April 1989 indicated that during the day, the stream channel bottom of Ahupu 'gulch was dry; however, at night, pools of water were observed to stand at several locations. This is taken as confirmation of ground water existence and high evapotranspiration demand.

SECTION THREE

Water Resources
and
Soil Conservation

Introduction

One of the most critical factors in the development of a water resource management strategy is the determination of the relation between land use, water supply and water quality. That land use impacts water supply is an inescapable fact that must be reconciled and factored into every resource management decision, as it forms the basis for effective watershed management.[1] For Kaho'olawe, where the impacts of past and present land use on surface and ground water supply are dramatic, water management will invariably involve land use strategies which facilitate both soil and water conservation.

Presently, runoff from an important archaeological area, the "hardpan", moves as overland or sheet flow over the surface, washing archaeological sites and foundation soils downslope. Over 500 archaeological sites and 2,000 features on the island face obliteration as a result of the severe state of water-induced soil erosion on Kaho'olawe. Moreover, as the soil is lost, the medium for vegetation growth is diminished. Hence the capture of soil is key to the retention of moisture, the establishment of a vegetative cover and to the control of water as it moves downslope. Wind erosion, long blamed for the removal of soil, did most of its work around the turn of the century. Both wind and water-induced soil erosion now combine as primary agents of soil loss and landscape change on Kaho'olawe.[2]

Erosion control on Kaho'olawe is mandated by a legal decree and memoranda of understanding between the State and the U.S. Navy.[3] In addition, Maui County, within which Kaho'olawe lies, envisions the return of the island to the State of Hawai'i and the development of Kaho'olawe as a cultural park. Some landscape stability must be achieved if these uses are to be accommodated. Kaho'olawe's landscape would be simply too unstable if no action were taken to arrest soil erosion. For instance, roads continually need repair, walking is difficult, if not dangerous in many areas as a result of soil instability.

To demonstrate the link between water management and soil erosion control and management, and to demonstrate appropriate technologies, the Kaho'olawe Water Study included provision for the development of a number of projects involving soil and water conservation. This section describes the theoretical basis for and results of soil and water conservation demonstration project work, and is intended to provide a foundation for the formation of a water development plan for Kaho'olawe, discussed in Section IV of this report.

Notes

[1] The subject of land use impacts on water supply has received a considerable amount of attention in recent years, as watershed managers strive to predict and to minimize the impacts of land use on water supply and quality. Community planning strategies are more often incorporating management tools designed to account for land and water use relationships.

[2] There is a current debate among researchers as to the primary agent of erosion: wind or water. It is likely that both wind and water erosion persist to different degrees in different areas of Kaho'olawe. Where there is sufficient soil, of small particle size, or where heavily used roads exist, wind erosion is significant. However, on some of the hardpan soils, water is the primary agent inasmuch as wind did its work long ago. The impact of both wind and water as agents in the process of soil loss is also likely determined by regional variations in climate, soil types, vegatation, and topography. There has been a tendency in the past to treat Kaho'olawe as one land mass with uniform conditions throughout. However, there is a need to recognize the existence of regional variations. It is imperative that resource managers begin to move beyond this debate to gather more empirical data to understand the combined effects of the two primary erosive agents and develop integrative management approaches to effectively control the erosion.

[3] See Chapter 1.

Chapter 6

Soil and Water Conservation

Principles of Soil Conservation: Management and Control of Gullies

The link between past descriptions of Kaho'olawe as a vast meadow land and its present barren appearance is soil erosion. Stearns (1940) estimated that between the years 1880 and 1939, between 6-8 feet of topsoil was lost from some 14,000 acres of Kaho'olawe's summit. The mechanisms of erosion and dissection of Kaho'olawe's landscape following this devastating loss of soil are key factors in identification of strategies to prevent further soil loss.

Water-induced soil loss on Kaho'olawe results from four major processes: 1) overland flow, 2) gully development and enlargement, 3) mass wasting of channel side slopes, and 4) stream bank erosion. The relative balance of each of these processes within each watershed varies on Kaho'olawe; however, overland flow and gully development dominate the range of soil erosion processes.

Soil Loss by Overland Flow

As described in the surface water section, overland flow, or sheet flow, dominates the upper portions of most watersheds on Kaho'olawe. This is a critical process on Kaho'olawe, inasmuch as the generation of most overland flow occurs in areas with a great density of archaeological features.

Soil loss resulting from overland flow is generally calculated using the Universal Soil Loss Equation (USLE) or a modified version developed for site specific conditions. The equation was developed by the U.S. Soil Conservation Service (SCS) and has wide application in Hawai'i.[1] The USLE is useful in evaluating the need for conservation strategies and guides the development of the practices and methodologies used in reducing soil erosion. The equation applies strictly to rill and sheet erosion; separate estimates of gully and streambank erosion are evaluated using other tools.[2]

The soil loss equation is:

$$A = R\,K\,L\,S\,C\,P$$

where:

A is the computed soil loss, in tons/acre/year
R is the rainfall factor
K is the soil erodibility factor
L is the slope-length factor in feet
S is the slope-gradient factor, percent slope
[together L & S combine to form the LS factor[3]]
C is the cover and management factor
P is the erosion control practice

The USLE was applied to Kaho'olawe watersheds in order to derive an estimate of annual soil loss. The analysis was also used to identify the most significant component of soil loss as a means of guiding soil erosion control strategies.

The rainfall factor is derived from an analysis of rainfall characteristics, and describes the relative erosive energy of precipitation. Since most of the storms that occur on Kaho'olawe consist of high intensity rains, the erosive energies of impact are considerable. The rainfall factor value for Kaho'olawe was determined using rainfall information derived by SCS from comparable climactic areas on Maui and Lana'i. These figures are shown in Table 6.1.

The soil erodibility factor, K, describes the relative erodibility of soils. Data have been tabulated for numerous soil groups in Hawai'i. Highly erosive Kaho'olawe soils, including considerable badland topography, are similar to soil types found on Maui and Lana'i, and K factors ranging from .17 to .49 are also shown in Table 6.1.

The length-slope (LS) factor is derived from field measurements of slope lengths and slopes as well as by analysis of topographic maps of the region. The LS factors for various conditions are tabulated by SCS. The headwaters of many Kaho'olawe watersheds originate in the hardpan region and many have slope lengths greater than 1,000 feet and slope gradients of 10%; data for selected watersheds are presented in Table 6.1.

The cover and management factor, C, is also derived from SCS developed tables, and describes the percent and type of ground cover in the area of interest. C values for permanent pasture and idle land and for bare soil (C value = 1) were used in the analysis of Kaho'olawe conditions (Table 6.1).

Table 6.1. Universal Soil Loss Equation Factors for Selected Watersheds, Kaho'olawe, Hawaii

Watershed	Area	R	K	LS	C	P	S
Hakioawa	755	200	.49	4.33	1	1	10%
Wa'aiki	218	200	.37	3.87	1	1	12%
Papakaiki	538	200	.37	4.12	1	1	9%
Kaulana	685	200	.28	3.14	1	1	8%
Kuhe'eia	228	200	.28	4.42	1	1	4%
Ahupu	1,638	200	.49	2.13	1	1	6%
Kaukamoku	768	200	.37	1.70	1	1	7%
Wai Honu	1,267	200	.49	1.01	1	1	4%
Kanaloa	1,267	200	.49	1.01	1	1	7%
Kaukamaka	1,005	200	.49	5.71	1	1	12%

Finally, the erosion control practice P describes the type of and management practice in effect in the area of interest and relates the practices to the slope of the land surface. The P value for no erosion control practice is 1 and is used in the analysis of soil loss on Kaho'olawe.

The annual soil loss for selected watersheds on Kaho'olawe as indicated by the soil loss equation are shown in Table 6.2. The rates range from a low of 57 tons/acre per year to over 500 tons/acre/year.

High soil erosion rates are illustrated by the example of Hakioawa watershed, for the conditions:

$R = 200$
$K = .49$
$L = 1000$ feet
$LS = 4.33$
$S = 10\%$
$C = 1$
$P = 1$

The annual soil loss, in tons per acre per year is:

$$A = 200(.49)(4.33)(1)(1) = 424 \text{ tons/acre/year.}$$

For the approximately 300 acres of the Hakioawa watershed presently impacted by sheet flow, the soil loss as **a result of sheet flow alone is over 127,200 tons per year.**

Table 6.2. Annual Soil Loss from Selected Watersheds Kaho'olawe Hawai'i, 1989

Watershed	Area (acres)	Rate (tons/acres)	Total (tons)
Hakioawa	755	424	320,120
Wa'aiki	218	286	62,384
Papakaiki	538	304	163,552
Kaulana	685	176	120,560
Kuhe'eia	228	248	56,544
Ahupu	1,638	208	340,704
Kaukamoku	768	125	96,000
Wai Honu	1,267	57	72,219
Kanaloa	1,056	209	220,704
Kaukamaka	1,005	559	561,795
		Total Annual Soil Loss:	**2,014,582**

Mechanisms of Gully Formation

An additional principal component of increased soil loss on Kaho'olawe is headward and lateral advance of drainages through gully development. Many areas of Kaho'olawe now suffer from increased gully formation, with instability signaled by the development of numerous small rills on the land surface. Advance and enlargement of gullies occurs by means of three processes: 1) headcut advance, 2) channel down cutting and, 3) side slope mass wasting (Heede, 1979; Leopold et al., 1964). The headward advance of a gully is measured by its linear extension over time; channel down-cutting is represented by increasing gully depth, and side slope mass-wasting results in gully widening. All three processes--which have different conservation remedies--contribute large quantities of soil to stream flow. A typical Kaho'olawe gully is presented as a schematic diagram and photo in Figure 6.1 and 6.2, respectively.

Gullies may be classified as **continuous** or **discontinuous**. The difference in the gully types has significant implications for the calculation of stream flow,

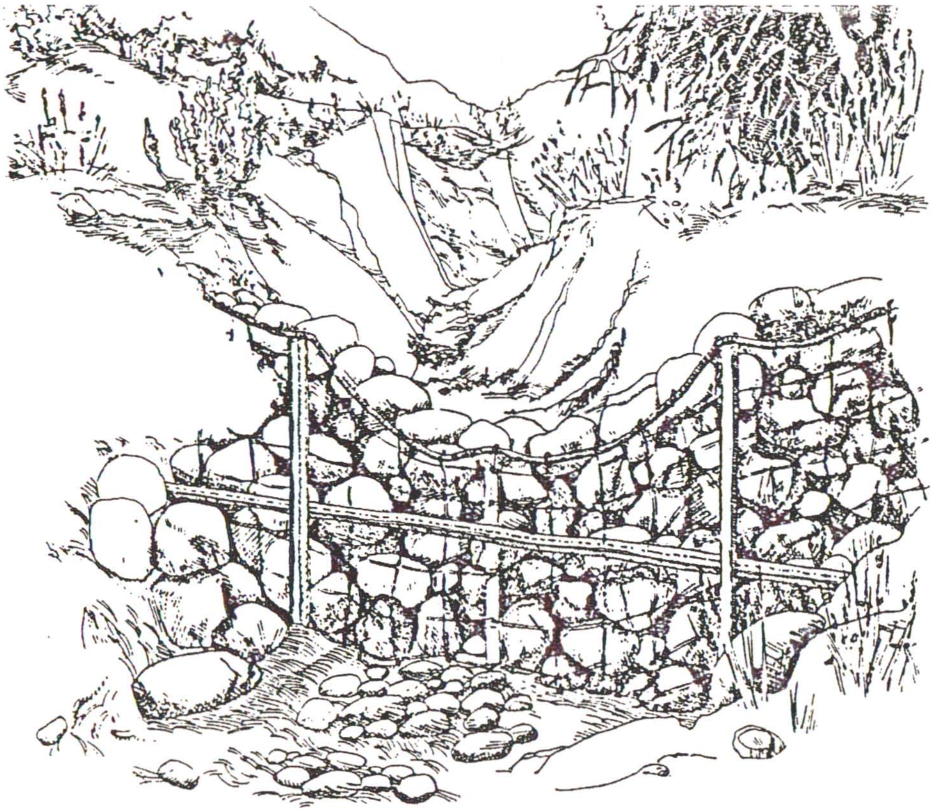


Figure 6.1. Schematic diagram showing a typical Kaho'olawe gully. Kaho'olawe gullies have steep vertical banks and are marked by a vertical headcut.

Figure 6.2. Photo of a typical Kaho'olawe gully located on the northeast side of the island.

overall channel gradients and for the development of gully management strategies. Briefly, continuous gullies are more amenable to hydraulic description than discontinuous gullies, because a continuous gully has a continuous channel with predictable hydrologic responses.[4] Discontinuous gullies, because they appear and disappear, are difficult to analyze hydrologically. In general, the upper portions of the watersheds of Kaho'olawe and those areas used as bombing targets are characterized by discontinuous gullies.

Discontinuous Gullies. A diagram illustrating the development of discontinuous gullies from small rills on the land surface is presented as Figure 6.3. The smallest channels on the land surface, the ephemeral rills, which carry water only during storms, commonly develop in a parallel pattern. Rills can appear anywhere on the land surface, and the head of the rill does not necessarily extend into the watershed divide. As shown in Figure 6.3 (A), a small divide initially exists between each rill. The two parallel and adjacent rills, when seen in cross section, will usually differ slightly in elevation and depth, as demonstrated in Figure 6.3 (B).

MECHANISMS OF GULLY FORMATION

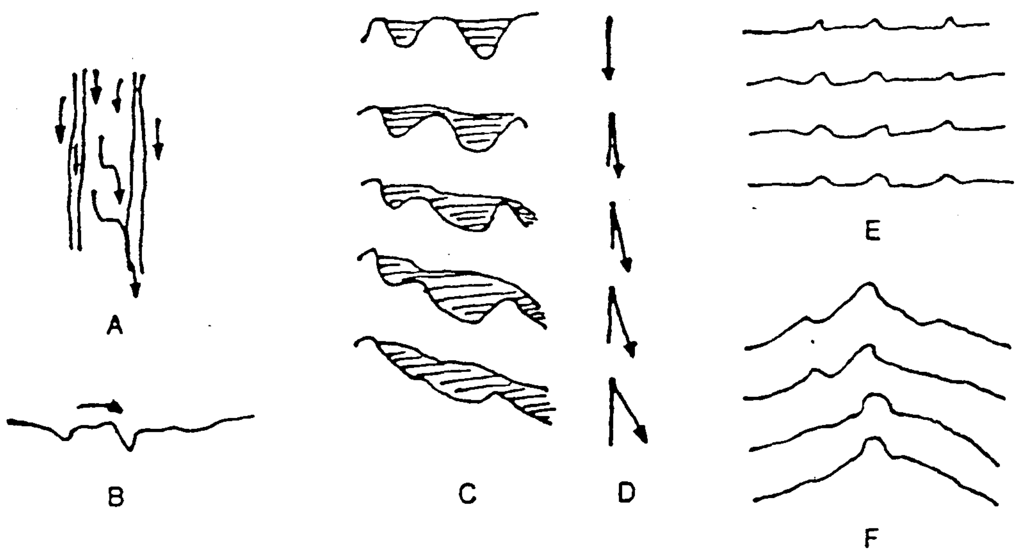


Figure 6.3. Diagram showing the development of gullies from rills. In (A), a plan view illustrates two small rills parallel to eachother on slope. (B) shows a cross section, illustrating that one rill may be slightly deeper than the other. As water moves down the slope through the rills, a lateral component of flow develops if the depth of flow is great enough to overtop the ridge between the rills (C, D). The rill divide is then broken down and a gully begins to develop. (E) illustrates the shape of the topographic contours as rill develop into gullies (After Leopold and Miller, 1965).

During a heavy storm, when overland flow occurs to a sufficient depth to fill adjacent rills and to overtop the intervening divide, the water develops a lateral component of motion toward the slightly larger and lower rill, progressively breaking down the inter-rill divide [Figure 6.3 (C)]. At this point, a knick-point, or headcut, develops. The water that is channeled into the latter rill develops more erosive ability and deepens or widens the headcut. Eventually, the original rill pattern is obliterated. The process is similar to stream capture. The depth of the discontinuous gully generally decreases rapidly downstream, and an alluvial fan is formed where the gully intersects the valley. When water reaches this point, it spills further downslope below the alluvial fan, causing another knick-point or headcut to develop. This knick-point migrates upstream to join the original rill and then deepens this knick-point. Headward advance of the knick-point, or headcut, thus deepens the gully, turning ephemeral rills into gullies.

Discontinuous gullies also form as a result of **soil piping**, a process by which the movement of water through fine-grained material actually transports fine particles away from their original place of deposition and leaves voids or channels beneath the soil surface. Tree roots, rodent holès and other processes provide the avenue through which water can enter the subsurface and produce a small pipe through which the water is eventually channeled. Montmorillonitic soils, which shrink and swell upon drying and wetting, also provide a mechanism for the formation of soil pipes. As the soil is carried away by water running through holes in the ground, support for the overlying soil is removed, the soil pipe collapses, forming a headcut. Soil piping is also known as pseudokarst, tunneling erosion, and pothole erosion, and is particularly prevalent in montmorillonitic soils. Figure 6.4 schematicallly illustrates a typical soil pipe. Figures 6.5A and 6.5B illustrate a series of soil pipes on Kaho'olawe, demonstrating that soil piping is a major erosive process on Kaho'olawe.

The underlying mechanisms for discontinuous gully formation are not clear. Research suggests that a variety of factors, including a break in slope gradient, overly steep slope gradients, soil piping collapse, climatic factors, and underlying geology, affect the formation of discontinuous gullies. On Kaho'olawe, the existence of bomb craters and surrounding impact areas is also a factor in discontinuous gully formation on certain areas of the hardpan.

With regard to soil piping processes, the existence of thousands of small, detonated 6-inch holes on the hardpan area provides a man-made hole into which overland flow may be channeled and the process of soil piping collapse initiated. The holes were detonated in order to plant tamarisk trees;, however, there are over 8,000 holes that have been detonated but not planted.

An aerial photograph of the Hakioawa watershed headwaters, taken after a major rain storm in September 1988, suggests possible subsurface movement of water from one detonated hole to the next (Figure 6.6). Note the regular, straight line of damp soil material following the course of detonated 6 inch holes.

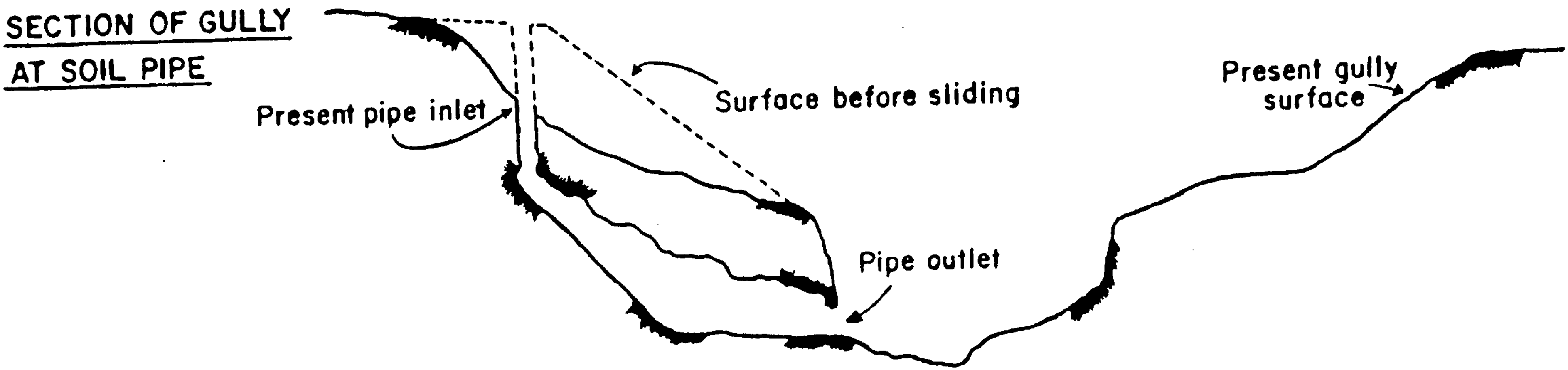


Figure 6.4. A diagram of a soil pipe. The top left shows the pipe inlet, where water has burrowed down into the soil. The pipe outlet is slightly above the gully floor, where outflow from the pipe has scoured the floor of the gully (From Heede, 1971).

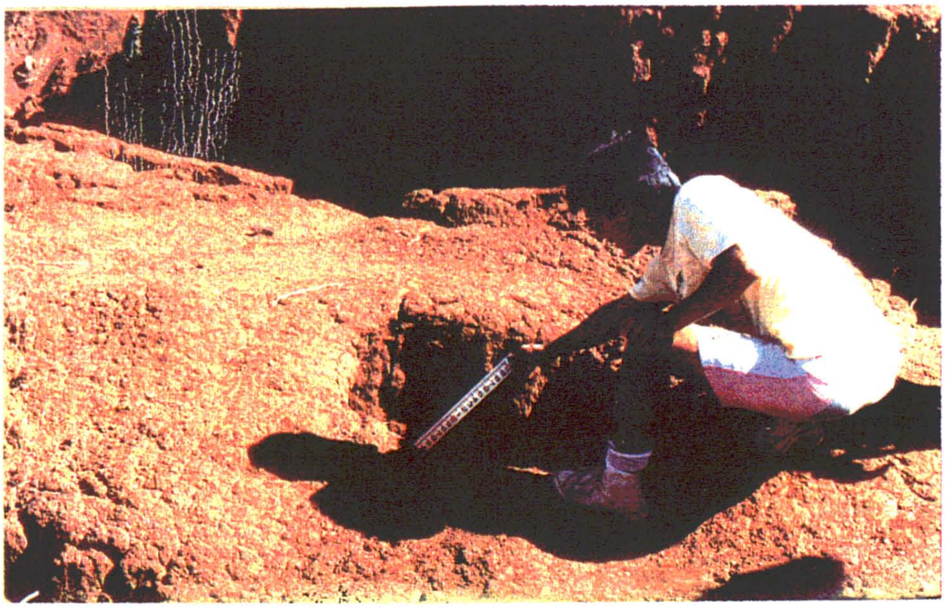


Figure 6.5A (*above*). A photo showing the top opening to a soil pipe located at the Mauka I work site. Much like the schematic in Figure 6.4, the path of the soil pipe ran down through the surface and ended just above the floor of the gully located beyond the edge of the hardpan surface. As shown in the photo, the length of the pipe extended well beyond the 11-foot survey rod dropped into the opening (Photo by Protect Kaho'olawe 'Ohana, September, 1988).

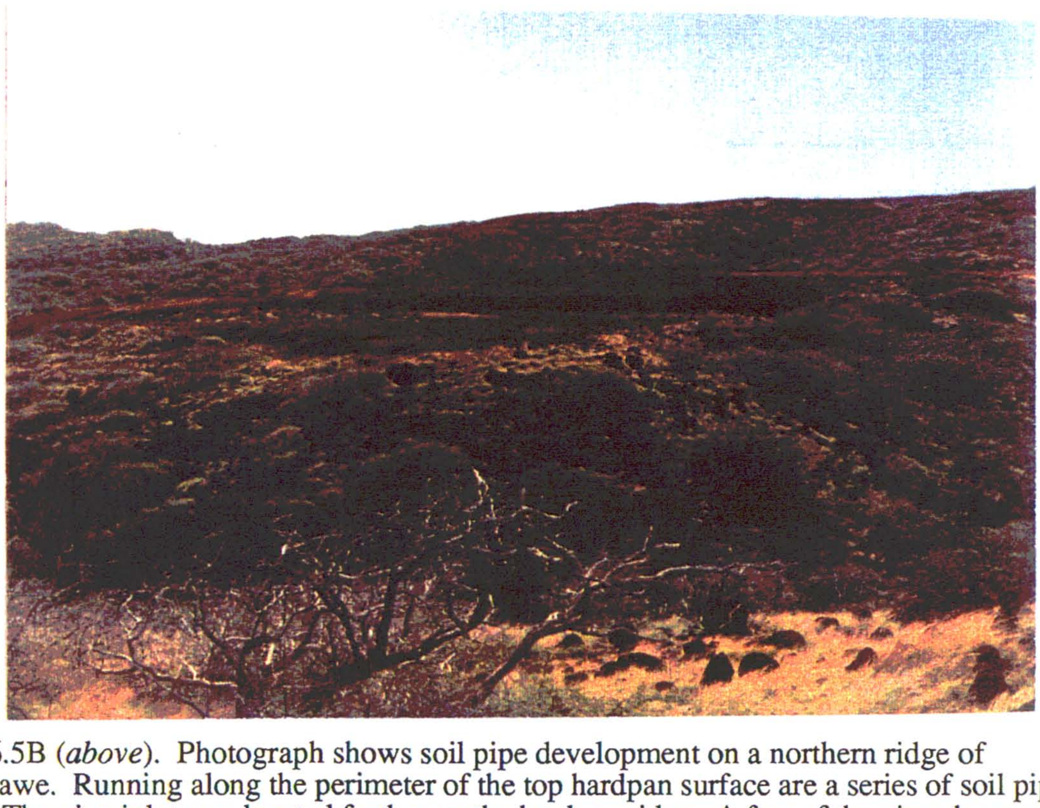
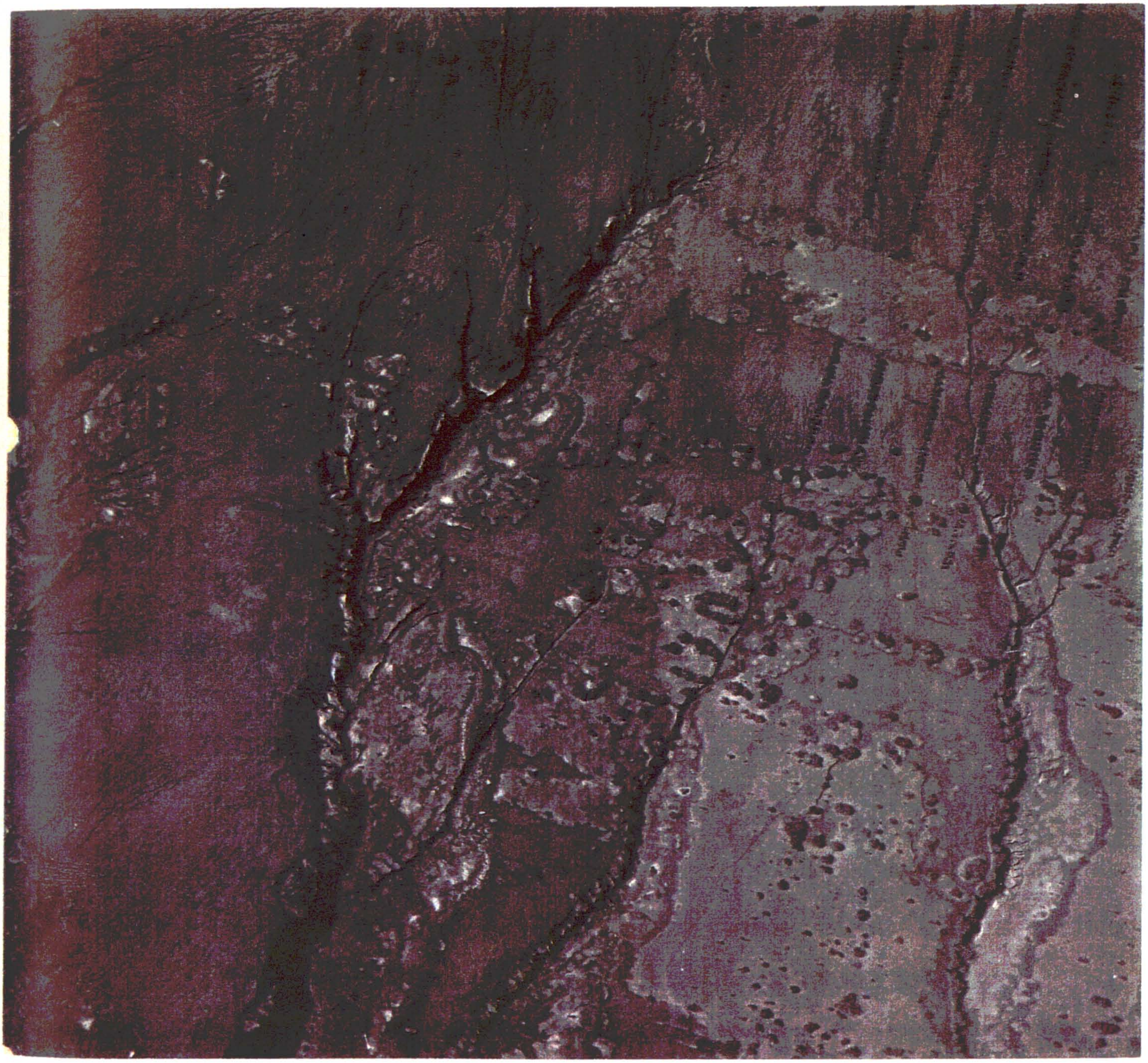


Figure 6.5B (*above*). Photograph shows soil pipe development on a northern ridge of Kaho'olawe. Running along the perimeter of the top hardpan surface are a series of soil pipe outlets. The pipe inlets are located further up the hardpan ridge. A few of the pipes have partially collapsed (to the left of the outlet row) forming headcuts which are dissecting the hardpan surface (Photo by Protect Kaho'olawe 'Ohana, September, 1988).

Figure 6.6. Aerial photograph of Kaho'olawe summit (Lua Makika) showing possible additional soil pipe development near and surrounding unplanted tree lines. Soil pipes would develop in and surrounding the 6 inch holes blown in the surface by the Navy. Note the pattern of gullies which emerge from the tamarisk treelines (Photo by R. M. Towill Corporation, September, 1988).



A chain of discontinuous gullies can be expected to fuse together into a single continuous gully or continuous channel. Heede (1971) describes the rapidity with which this change can occur. A photo presented as Figure 6.7 show gullies dissecting the flat hardpan surface.

Figure 6.7. Photograph showing rapid advance of headcuts observed during the Kaho'olawe Water Resources Study field season. Prior to the rainy season this segment of the hardpan surface was relatively flat. The following spring (5 months later) the photo shows the hardpan is dissected with a network of gullies. (Photo by Protect Kaho'olawe 'Ohana, March 1989).

Continuous Gullies. Continuous gullies begin with many extensions into the headwater area, and are characterized by an abrupt headcut. These gullies gain depth rapidly and continue downcutting until the mouth of the gully is reached. Continuous gullies are more subject to hydraulic description than discontinuous gullies because it is possible to quantify flow amounts and velocities, contributing areas and other factors. Continuous gullies evolve by headcut advance, however, the evolution of continuous gullies can also result from channel downcutting and side slope mass-wasting.

The behavior of the headcut in a continuous gully is governed by the discharge regimen and by the structure and composition of the bed and bank materials of the stream. Studies indicate that in non-cohesive materials an oversteepened slope will be reduced or flattened at a rate proportional to the rate of sediment transport, transport being a function of particle size and flow (Leopold et al., 1964). In homogeneous cohesive materials, studies indicate that under certain conditions a knick-point or headcut will retreat by maintaining a vertical face. For a given depth of flow, if the initial height of a vertical face or abrupt drop in a channel bed is such that critical flow is attained at the knick-point and a "plunge pool" or hydraulic jump occurs at the base of the face, the vertical face will retreat upstream. The vertical face is maintained on Kaho'olawe because the material making up the vertical face has a resistance to shear stress greater than its resistance to the stress provided by flow conditions. Additionally, the vertical face is maintained because the flow is sufficient to transport the eroded material from the base of the headcut downslope.[5]

One of the major controls on channel downcutting is the base level that the gully, or stream channel, seeks. There may be "local base levels" defined by the levels to which portions of channels flow, such as lakes, falls or bedrock ledges. Or base level may be that major body of water to which distal portions of the channel system seek, such as the ocean. Gully downcutting will seek local bedrock base levels, and changes in that base level will affect the development of the gully channel network above the point in question. For Kaho'olawe, the large gully network developing on the hardpan of Hakioawa watershed is seeking a local bedrock ledge that is 100 feet below the present land surface, indicating that there is still a large soil column left on Kaho'olawe and that the forces encouraging channel downcutting are great.

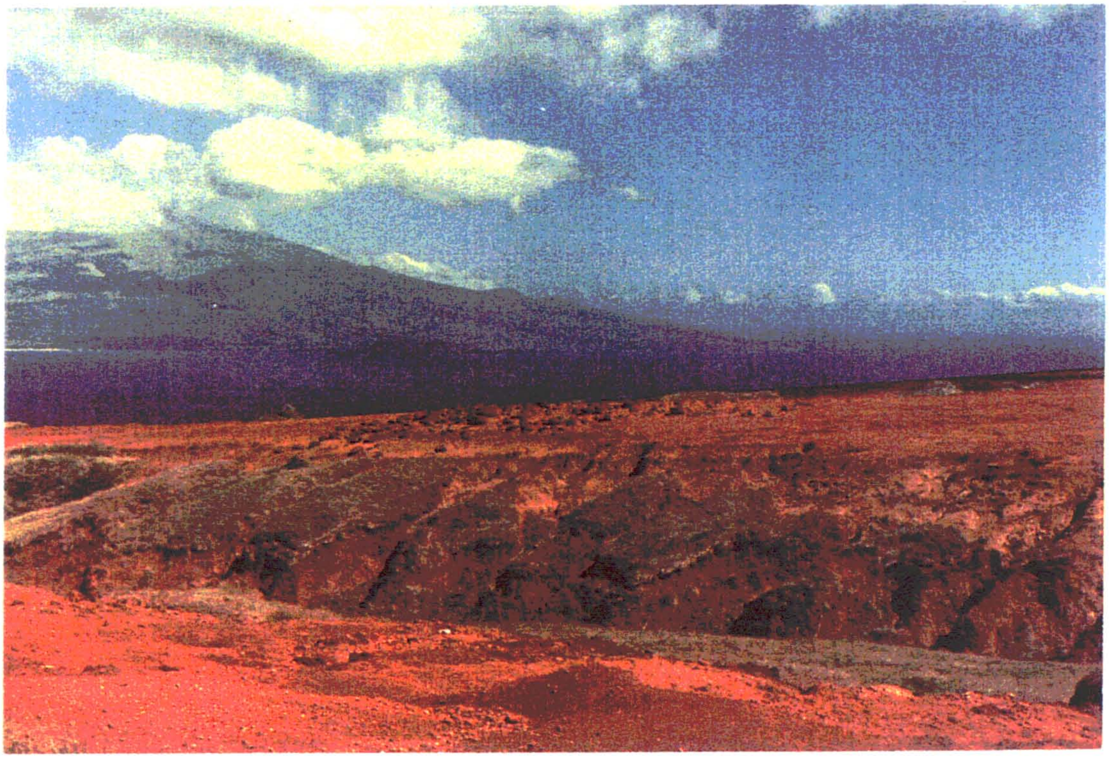
Inasmuch as gully side slopes are steep, and stream flow within gullies tends to undercut banks, gully side slope mass-wasting is the other significant process affecting gully development on Kaho'olawe. Figure 6.8 presents a photo of a portion of Hakioawa gulch showing mass-wasting on the side slopes.

Techniques of Gully Control

Given the mechanisms of gully formation identified above, effective gully control must stabilize both the channel gradient and the channel headcuts. The long term goal, vegetation growth, acts to stabilize both channel headcuts and downcutting. Short-term measures must therefore conserve both soil and moisture in developing a medium for eventual plant growth.

The development of gully control measures must be based upon a fundamental understanding of the hydrology of the region and the mechanisms and characteristics of water flow to be expected. It is not possible simply to place a structure in a gully; the entire gully and its contributing watershed behaves as a system and strategic locations must be chosen.

Figure 6.8 (*below*). Photograph showing the mass-wasting of the side slope mass-wasting of this large gully, one of the three main tributaries in the Hakioawa watershed. The gully is several hundred feet in depth. Notice the large remaining grassy patches literally dropping into the gully through the process of mass wasting (Photo taken by C. Vandemoer, March 1988).



Engineering measures such as check dams, erosion control netting and headcut control structures are used to stabilize gully gradients at critical channel locations, while watershed restoration procedures outside the channel, such as terraces and revegetation, assist in the reduction of overland flow and increase infiltration. For Kaho'olawe, check dams, headcut control measures, and revegetation strategies formed the core of water study demonstration projects.

Check Dams. Check dams are porous structures built across a channel at certain hydraulically-defined locations. Check dams are designed to capture sediment and pass water, although some moisture is retained in the soil behind the check dam. Additionally, check dams serve the purpose of reducing the channel gradient, thereby changing the response of the drainage network above the dam and lessening downcutting response. Finally, check dams act to slow the velocity of water, thereby reducing its erosive energy. There are many different types of check dams, ranging from loose-rock, wire reinforced structures to concrete. Figure 6.9 provides a schematic of two types of dam structures used in the study: a loose rock check dam and a wire reinforced check dam (photos of the constructed dams appear later in the chapter).

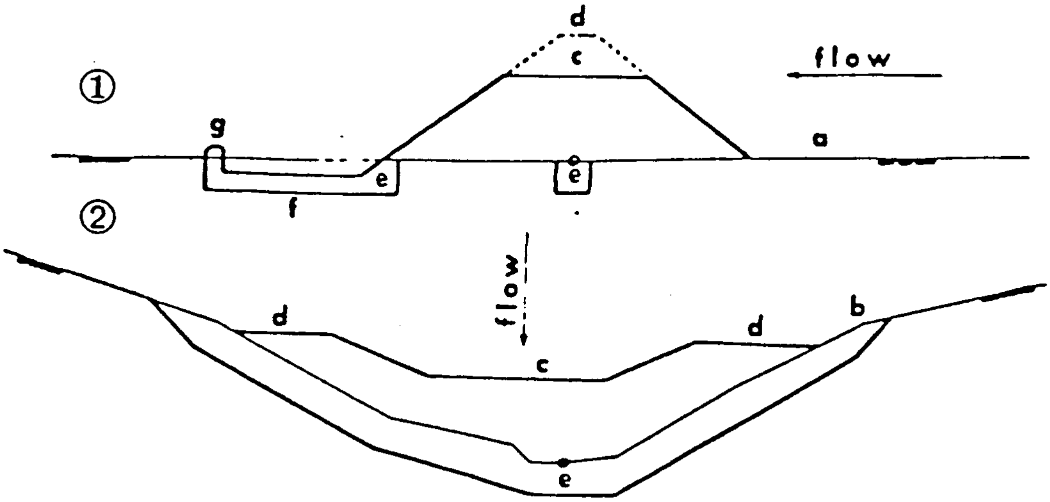


Figure 6.9A. Construction plans for a loose-rock check dam.
① represents the section of the dam parallel to the centerline of the gully.
② represents the section of the dam at the cross section of the gully. **a** = original gully bottom; **b** = original gully cross section; **c** = spillway; **d** = crest of freeboard; **e** = excavation for apron; **g** = end sill.

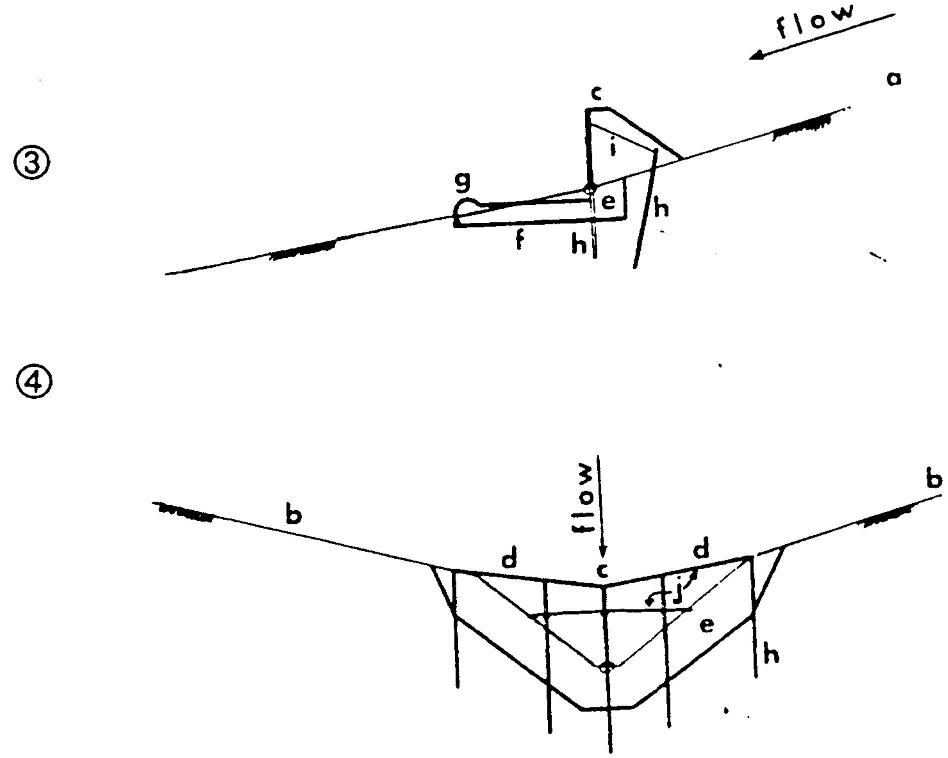


Figure 6.9B. Construction plans for a single-fence rock check dam.
③ represents section of the dam parallel to the centerline of the gully.
④ represents the section of the dam at the cross section of the gully. **a** = original gully bottom; **b** = original gully cross section; **c** = spillway; **d** = crest of freeboard; **e** = excavation for key; **f** = excavation for apron; **g** = end sill; **h** = steel fencepost; **i** = guy wires; **j** = rebar.

The placement of check dams is influenced by a number of key factors relating to the form and evolution of the gully.[6] Failure to assess these factors in the placement or design of check dams results in structural failure or initiation of further gullying processes. The critical design features include:

- Contributing drainage basin area,
- Velocity of stream flow for various size storms,
- Total volume of stream flow for various size storms,
- Gully geometry: top width, bottom width, depth, channel slope, and
- Expected sediment load and ultimate objectives of gully control.

Analysis of these factors will lead to the appropriate design of a check dam, including its location, height, top width, bottom width, quantity of bank protection and type of dam (Heede, 1976). The check dam must be anchored well into the channel bottom and side slopes in order to be effective in soil erosion control. In addition, adequate upstream and downstream bank protection must be provided.

Check dams are constructed starting from the base of the watershed and working upstream. Therefore, local base levels must be identified and used as starting places. The location of upstream check dams is based on the upstream toe of the sediment deposited behind the lower check dam. This position is predicted in the equations developed by Heede, and is described as the check dam spacing.

Headcut Control Structures. Headcut control involves the mechanical reshaping of the gully headcut to more effectively drain water into the gully. To be effective, headcut control structures generally lessen the grade of the headcut and place rock materials at the headcut and down to the channel bottom. The rock materials, arranged in the configuration of an inverted filter (fine materials on the bottom), serve to lead water slowly down into the gully, thereby slowing the velocity and erosive energy of streamflow. A schematic diagram of a headcut control structure is presented in Figure 6.10.

Erosion Control Netting. Jute, or some other kind of fibrous netting, is often used to stabilize unusually steep slopes and to provide an anchoring mechanism for vegetation growth. Erosion control netting can also be used in the stream channel bottom itself to create minor vortexes that both drop sediment and slow the water down.

Revegetation. The establishment of vegetation on the land surface increases the infiltration of water into the soil. In addition, vegetation acts to slow the velocity of water. Selection of vegetation types as aids to soil erosion control must be based on their ability to withstand calculated flow velocities, to take advantage of moisture in the stream channel, and their ability to firmly root both channel bottom and bank sediments.

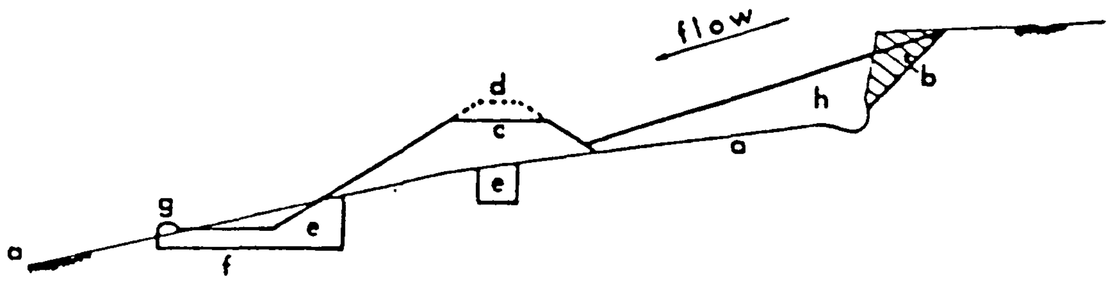


Figure 6.10. Example of a headcut control structure. The section of the structure is parallel to the centerline of the gully. a = original gully bottom; b = excavated area of headcut wall; c = spillway; d = crest of freeboard; e = excavation for key; f = excavation for apron; g = end sill; h = rock fill.

The gully headcut is mechanically altered to a lesser grade. Rock is then placed in the headcut as an inverted filter, with smaller material on the bottom and gradually increasing in size to the top of the structure. Angular rocks must be used as round rocks will roll with the water flow.

Watershed Restoration Measures. As indicated in the surface water section, the length of overland flow for many of Kaho'olawe's watersheds is considerable, enabling the development of highly erosive sheet flows, and eventually, channel flows. Watershed restoration measures aim principally at reducing the length of overland flow through terracing and other strategies that break the slope into shorter lengths. Watershed restoration works most effectively when using a number of combined strategies, such as revegetation, wind erosion control, and terracing.

The aforementioned strategies enable the development of comprehensive programs for soil stabilization and gully control. Identifying the mechanisms for gully formation within a watershed, and addressing these processes through engineering measures designed to stabilize the environment, permits realistic progress in island reclamation.

Implementation of Soil and Water Conservation Activities: Demonstration Projects

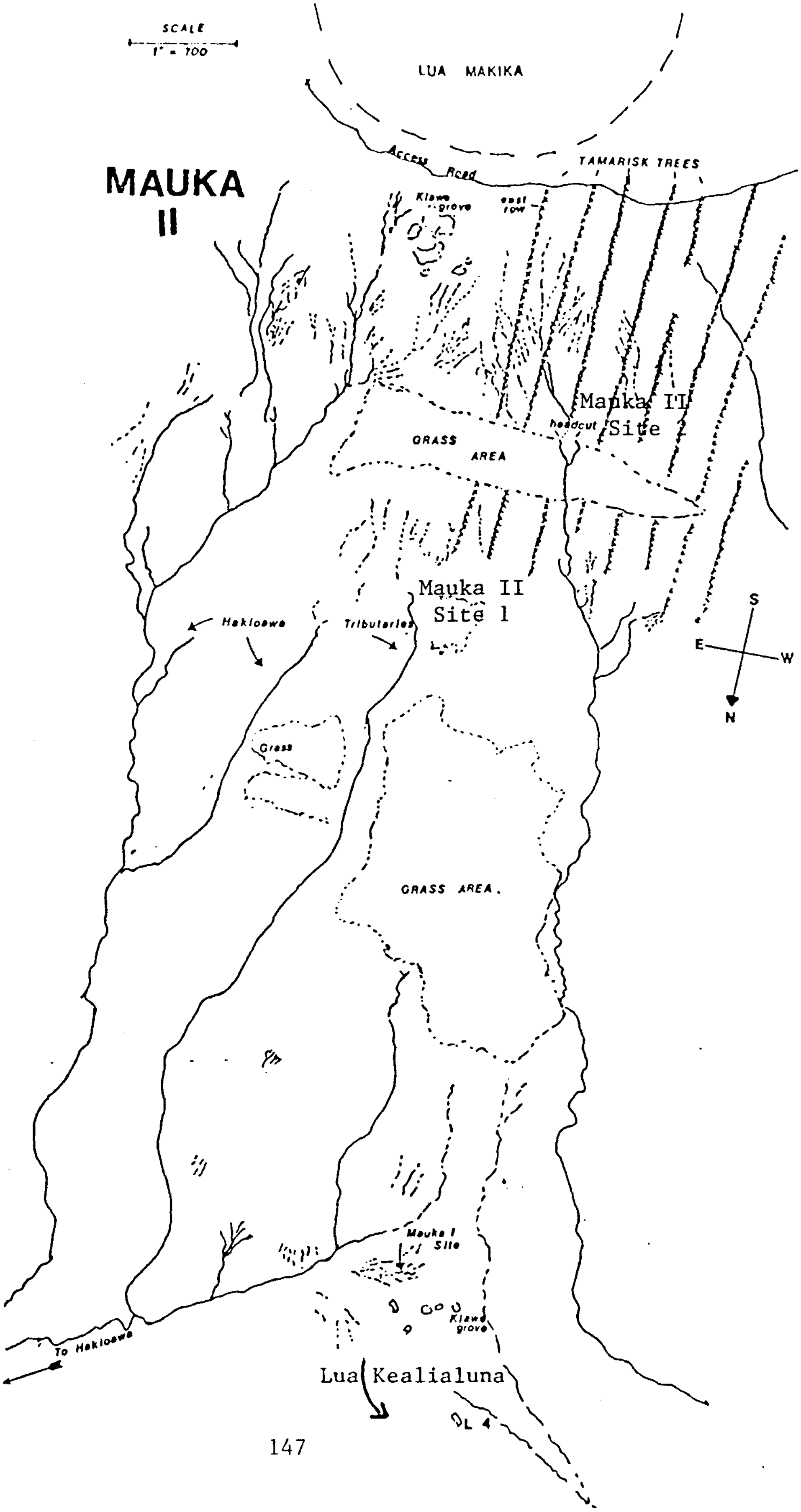
In recognition of the need to integrate land and water management strategies on Kaho'olawe, several small projects were designed to demonstrate techniques for achieving both land and water conservation. Building from the watershed approach identified earlier in this document, the Hakioawa watershed was chosen as a primary starting point. Demonstration work in each research area involved the comprehensive combination of a multitude of strategies to control soil erosion; that is, check dams were combined with headcut control measures, erosion netting and revegetation measures in an overall strategy to achieve regional landscape stability.

Two test areas within the Hakioawa watershed were chosen for construction of demonstration projects. The first area, named Mauka I, is located approximately 1.5 miles from the mouth of Hakioawa gulch on a northern tributary to the gulch and is approximately .5 miles southeast of Lua Kealialuna near archaeological site 651 (Figure 6.11). A series of gullies in a 2 square mile area subwatershed were chosen for the construction of several check dams, a headcut control structure, for the use of erosion control netting and for the development of a water supply as a means of integrating a planting project with soil erosion control.

The second area chosen for work, named Mauka II, is located on the hardpan, where one check dam and one headcut control structure were constructed. The first work area at Mauka II is located approximately .5 mile north of Lua Kealialuna on a small gully feeding the major tributary to Hakioawa gulch. A second site at Mauka II is located approximately .6 mile west-northwest of the hardpan check dam (Figure 6.11).

It is not often that immediate results are obtained from the installation of a structure, especially in the area of soil erosion control. However, during the course of the Kaho'olawe Water Study, several rainstorms produced large quantities of soil movement and project structures were observed to have a measurable beneficial impact on soil erosion in each study region. This enabled the immediate evaluation of the effectiveness of structures. The rainstorms also served to highlight the extent to which large quantities of soil continue to be removed from Kaho'olawe.

Figure 6.11. Map showing the location of the Mauka I and Mauka II study areas.



Mauka I Study Area

The Mauka I study area is a series of 6 gullies originating at the 650 foot elevation in a 2 square mile drainage area. The average depth of gullies in the region is 8 feet, with individual sections as small as 1 foot and as large as 15 feet in depth. Gully widths range from 1 to over 12 feet. There are several prominent headcuts in the region. The region consists of isolated patches of grasses, some shrub species, and clusters of kiawe trees scattered on rocky hillslopes. A map of the gully system is provided in Figure 6.12.

Runoff is derived from the eroded "hardpan" surfaces that blanket the region; the soil surface seals during rainstorms, promoting runoff. A considerable amount of overland flow is also generated. The region was selected because of the need to arrest headcut advancement of the gullies into and the possible capture of the Wa'aiki drainage system. Check dams, erosion control netting and headcut control structures dominated project activity in this region.

As a first examination of the gully system at the Mauka I site, project personnel measured the geometrical aspects of three major gullies, including top width, bottom width, total depth, slope and drainage area. The measurements were obtained for eventual use in hydraulic equations used to estimate the spacing, depth and height relations of check dams in the system. Table 6.3 presents gully geometry information for the Mauka I site.

Table 6.3. Gully Dimensions, Mauka I site, Hakioawa Watershed, Kaho'olawe
(values in feet)

Gully System*	Length	Top Width	Bottom Width	Depth	Slope	Number of Segments
1-North	226	8.0	5.1	5.7	8%	1
2-North	412	8.6	3.0	6.7	5%	22
3-North	677	20.4	7.6	11.4	8%	20
4-North	516	10.5	6.7	5.8	10.5%	20

Note: All values are average values based on the analysis of the gully in segments.
* See Figure 6.12 for location of gullies

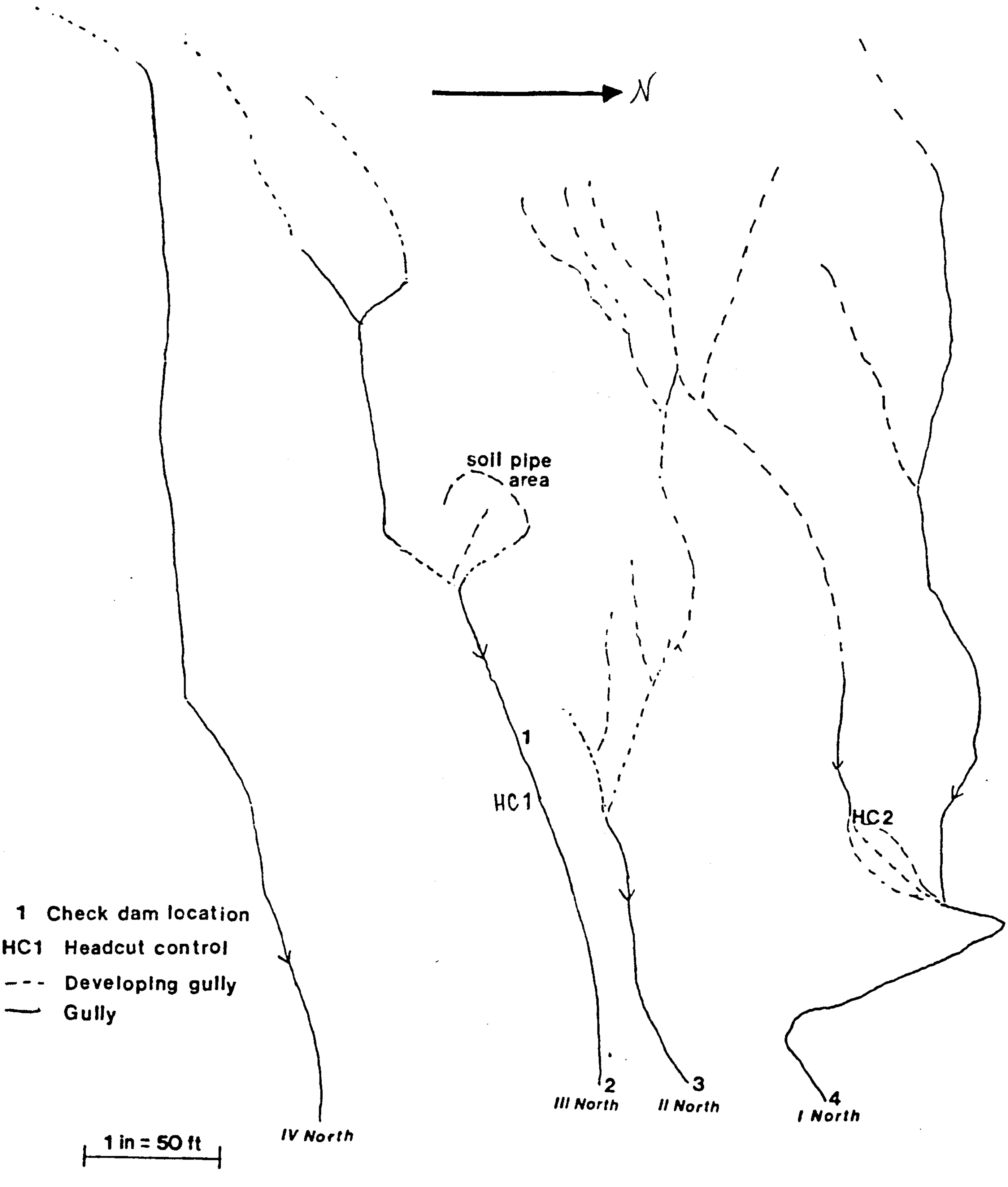


Figure 6.12. A map of the gully system for the Mauka I study area.

The second aspect of the analysis involved the identification of the depth and expected rate of storm runoff for different size storms for the region, given the drainage size and expected rainfall. These data were obtained using methods outlined in the surface water section, and are tabulated for the Mauka I watershed in Table 6.4. The largest rate of runoff expected in this region is 27 cubic feet per second (cfs), while the smallest is 6 cfs.

Table 6.4. Analysis of Runoff for Check Dam Structures for Mauka I Work Site

Drainage Area	Design Rainfall	Depth of Runoff/in rain	Peak Flow
7 acres	7.5 in	5.9 in	27 cfs
	3.0 in	2.0 in	6 cfs

Note: Curve Number = 89, Hydrologic soil group D

Given the previous analyses, the spacing, height and spillway relationships of the check dams were calculated using the method outlined by Heede (1976). Values used for each equation and resulting dimensions of the check dams at the Mauka I site are shown in Table 6.5. At the Mauka I area, check dam spacing is 120 feet, heights range from 2 to 5 feet and spillway lengths range from 1 to 2.8 feet. A total of six check dams were constructed at the Mauka I site, varying tremendously in size. Figure 6.13 and Figure 6.14 shows examples of two check dams constructed.

Table 6.5. Check Dam Spacing Mauka 1 and Mauka 2 Work Sites

Work Site	Effective Dam Height	Gradient (percent)	Spacing
Mauka 1[1]	4.2 ft	5%	120 ft.
Mauka 2[2]	3.4 ft	7%[3]	135 ft.

[1] For gully system identified as 2-North at the Mauka 1 work site, **see Figure 6.11.**

[2] The first segment, where this check dam is constructed, is 200 feet long. Additional analysis of other segments of this gully reveal check dam spacings varying from 65-120 feet.

[3] Actual deposition behind the Mauka check dam during the course of the project reduced the gully gradient from .5 to .2 percent; the sediment deposited 110 feet behind the check dam indicating close agreement between theoretical predictions and field conditions.

Figure 6.13. Photographs of loose rock check dams at the Mauka I work site. Loose rock check dams can vary tremendously in size as shown by these two examples.

Figure 6.14. Photograph of the wire reinforced check dam constructed at the Mauka I work site. Refer back to Figure 6.9 for design elements for this structure.

The largest check dam, Number 4 (see Figure 6.12), of loose-rock, wire reinforced construction, is in many ways the ideal type of check dam for Kaho'olawe conditions. Figures 6.15 through 6.17 demonstrate its construction, including the keying of the structure into the sides and channel bottom, the selective use of rock materials of different sizes, the wire reinforcement, and apron, bank and upstream bank protection measures. Over 15 tons of rock material were used in the construction of this check dam. Although many of the rocks were hand-carried and placed, the services of a private helicopter were employed to haul 1,000-pound loads of rock to check dam locations.

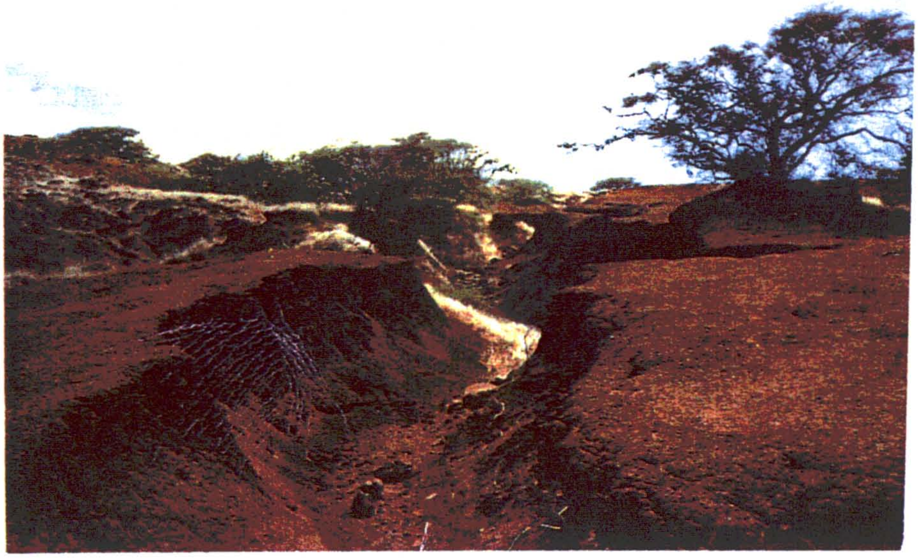


Figure 6.15. Photographs of gully before construction of the loose rock, wire-reinforced check dam at the Mauka I work site. This was the largest check dam constructed during the project, requiring over 15 tons of rock. The top and lower left photos provide an upstream view of the gully and the general surrounding hardpan surface. The lower right photo is a view looking downstream.

Figure 6.16. A series of 4 photographs showing the construction of key and wire frame for Check Dam #4 at the Mauka I study area. Note the keying in of the structure to the channel bottom and bank sides (*top and bottom*), the apron, upstream and downstream bank protection (*opposite page*). For a schematic of check dam design refer back to Figure 6.9B (photos by Ç. Vandemoer, October, 1988).

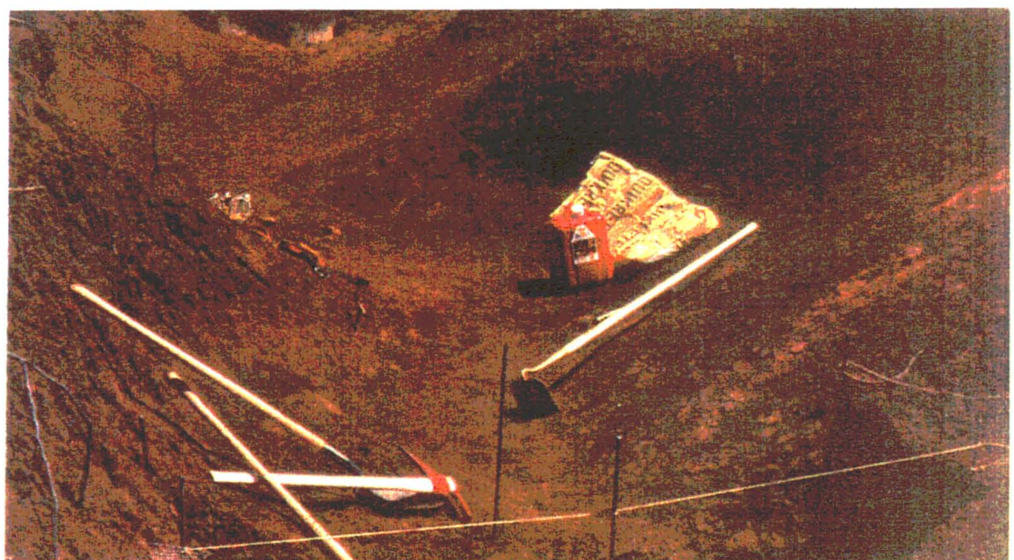


Figure 6.16 (Continued). View of frame for upstream bank protection (*top*) and downstream bank protection (*bottom*). Once filled with loose rock, bank protection prevents lateral erosion of side slopes around the check dam which could undermine the structure and also helps to channel flow through the check dam.

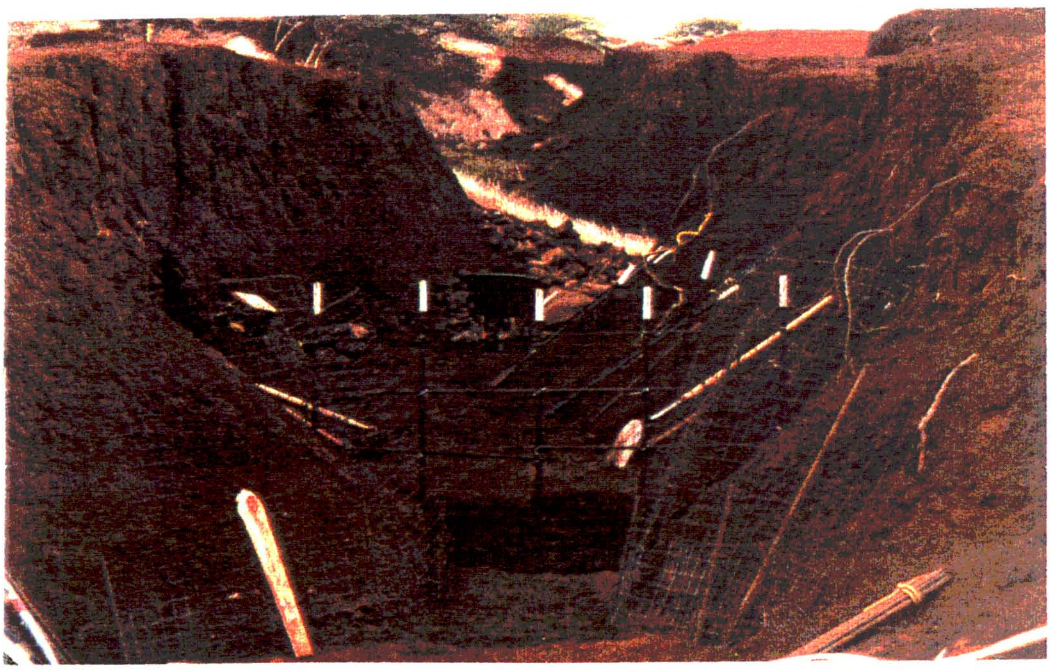


Figure 6.17. Photographs showing the completed check dam structure; downstream view (*top*) and upstream view (*below*). A porous structure, the check dam allows water to flow through, capturing sediment behind it. The photo below shows the completed spillway and apron. The apron, located at the base of the spillway prevents down cutting as water flows over the check dam.

A headcut control structure was also constructed at the Mauka I site, 30 feet downstream from checkdam Number 4. Locally derived rock materials were sized and used to construct an inverse filter of rock materials at the headcut (Figure 6.18). To prevent rocks from moving downstream under conditions of heavy flow, a fence was placed at the lower end of the structure and tied into the sidewalls with reinforcing bar. The upper edge of the headcut was lined with erosion netting, brand name ENKAMAT.

Figure 6.18. Photograph of headcut control structure, Mauka I study area (Photo by Protect Kaho'olawe 'Ohana, 1988).

Finally, to encourage deposition and to slow the velocity of flowing water in between the check dam and the headcut control area, erosion netting was anchored into the channel bottom. Figure 6.19 displays the arrangement of the installed ENKAMAT onto the channel bottom.

During and following the construction and installation of these structures, several rainstorms occurred on Kaho'olawe, providing first hand opportunity to review the effectiveness of the project's soil conservation structures. Figure 6.20 demonstrates the dramatic results of a single series of rainstorms (7.6 inches rainfall) which completely filled each check dam. The largest check dam captured over 3,600 cubic feet of soil, deposited soil more than 110 feet behind the structure, and raised the channel of the stream bed by 4 feet. The gradient of the stream bed changed from 5% to less than 3% as a direct result of the check dam, a reduction in the slope

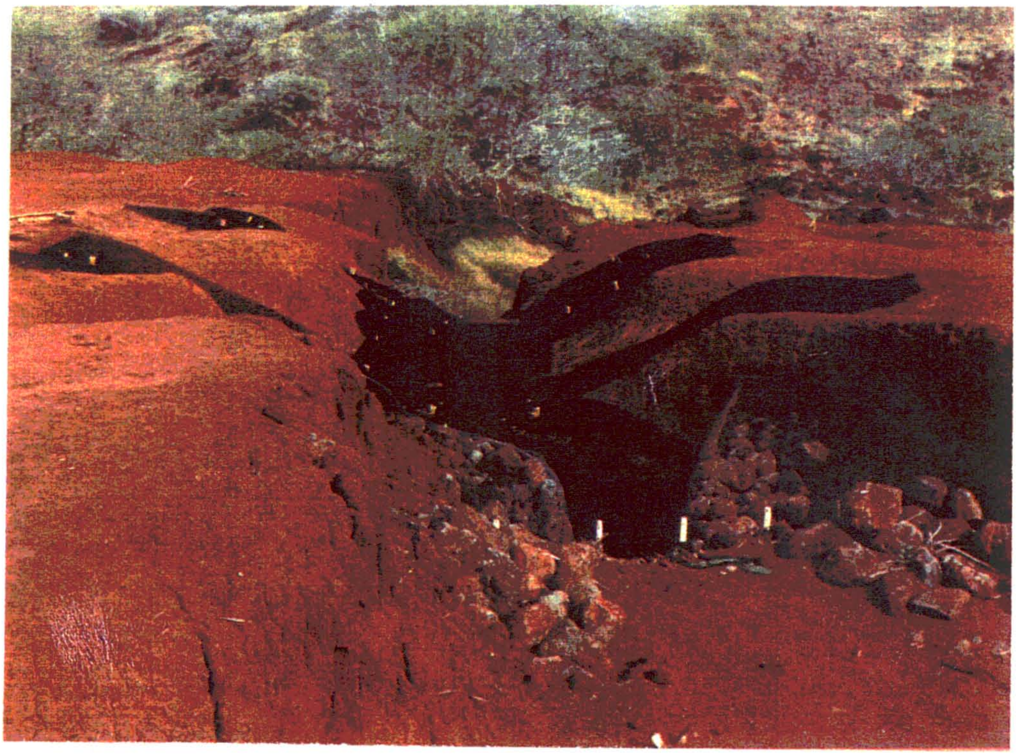
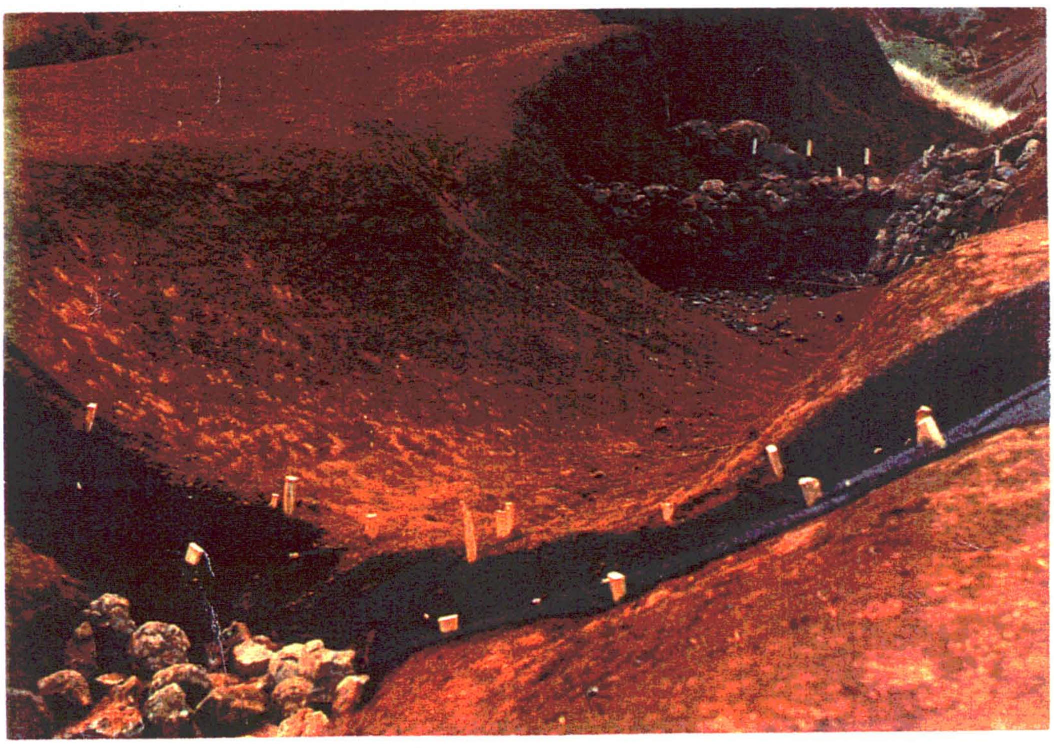


Figure 6.19. Photographs showing the placement and installation of erosion control netting at the Mauka I study area (Photos by Protect Kaho'olawe 'Ohana, 1988).



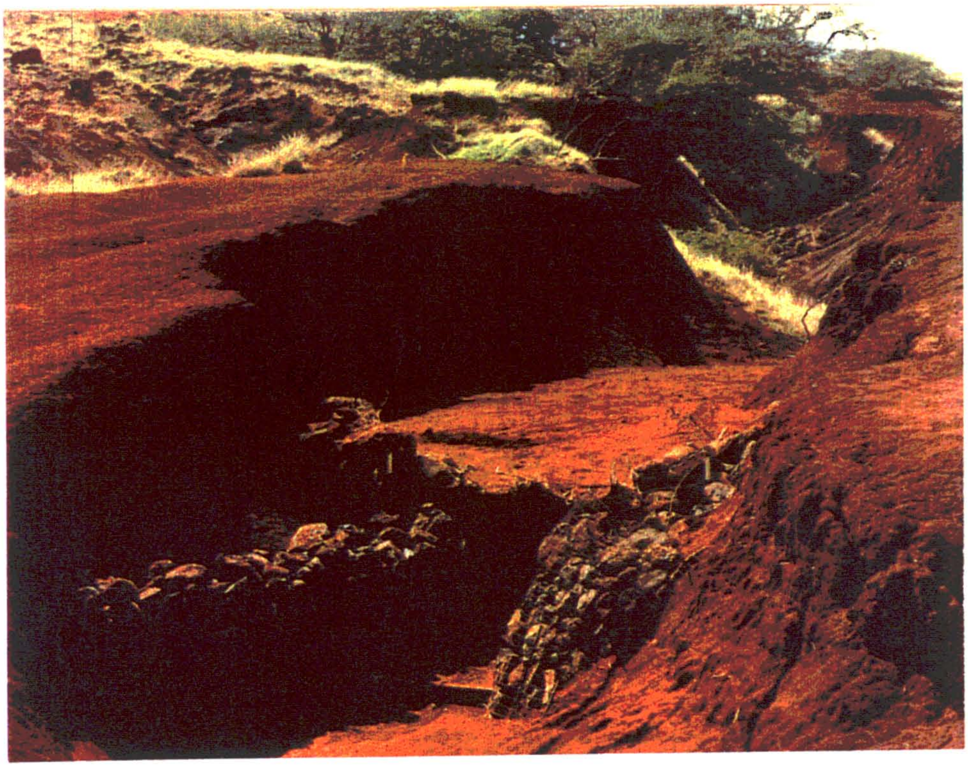


Figure 6.20. Photographs looking upstream (*above*) and downstream (*below*) showing the capture of over 3,600 cubic feet of soil behind Check Dam #4 at the Mauka I study area after one storm (7.5 inches rainfall). The capture of soil raised the stream channel level by 4 feet, reduced the channel gradient from 5 to 2.5 degrees, and backed up the soil behind the check dam for a distance of 120 feet upstream (Photo by C. Vandemoer, November 1988).

of 6 %. The theoretical analysis used in the development of this structure predicted the deposition of soil behind the check dam would be 120 feet, and that the stream gradient change in the section would be reduced to approximately 7% of its original value.

Damp soils behind the check dams revealed that moisture remained in the soil as long as three weeks after the storm. Further visits to the region in the subsequent four months after the filling of the check dams revealed the establishment of small strands of vegetation behind check dams and on gully sidewalls in the vicinity of the check dam.

The erosion control netting also affected soil loss and functioned as designed during the storms on Kaho'olawe between October 1988 and March, 1989. A layer of sediment over 3 inches in thickness was deposited within and above the ENKAMAT and bank erosion and undercutting has been markedly reduced as a result of the bank protection built into the entire project area.

Although the headcut control feature did suffer some loss of rock material as a result of considerable flow velocities generated during the 7.6 inch rainfall event in October, minor adjustments seemed to work well in further storms: soil is being trapped in the structure and the channel gradient slowly changed.

In February, 1989, members of the Protect Kaho'olawe 'Ohana planting crew planted 400 plants behind the check dam, and over 400 plants in the upper watershed of the same gully system. Return to the site in March 1989 revealed 90% survival of species in the gully, despite evidence of several flow events subsequent to planting. One hundred percent survival of plants in the upper watershed was observed. Photographs of the planting are provided in Figures 6.21 and 6.22.

The results of the work at the Mauka I site demonstrate promising construction techniques and strategies for gully management and control on a small watershed level. The combination of gully gradient control, headcut control, channel downcutting control through erosion netting, check dams and revegetation strategies work well to affect regional soil erosion. The successful results contrast sharply with other "check dam" techniques used on Kaho'olawe, such as tires and household and military waste, which have had little success with soil erosion control (Figure 6.23).

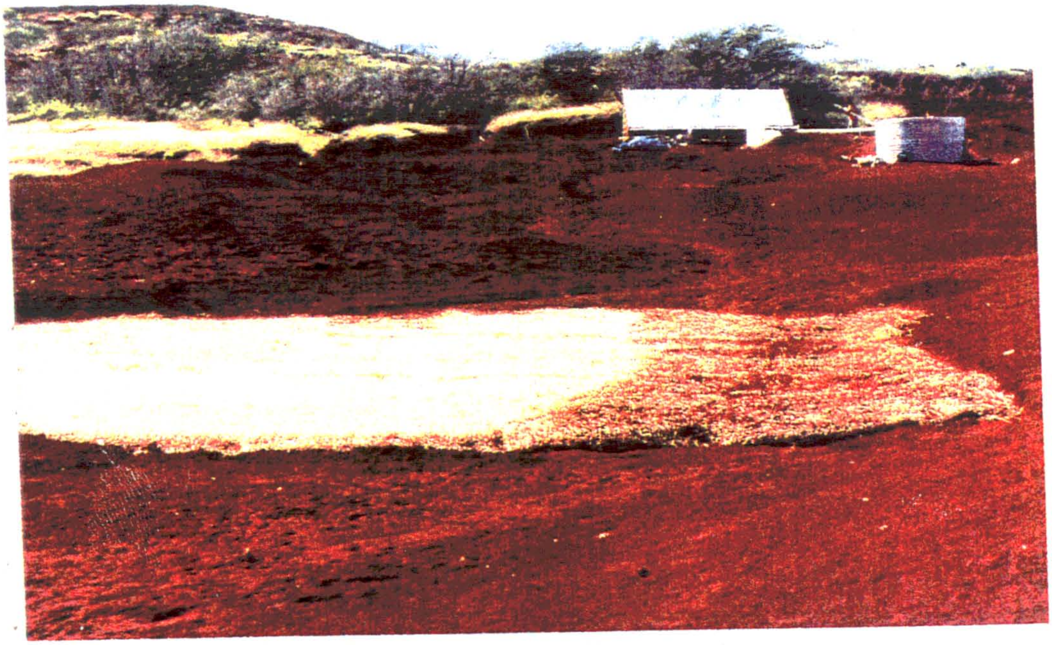


Figure 6.21. Photographs of Mauka I planting site. Figure 6.21A *(above)*: Site preparation involved hand tilling the soil and spreading of erosion control netting called Curlex. The catchment system which supplies water to the planting site through gravity feed is visible in the background.

Figure 6.21B *(above)*: The native strand vegetation (including ʻākulikuli, ʻilima papa and pāʻū-o-Hiʻiaka) that was planted in February 1989 are thriving after one year. The water distribution system was installed at the site and erosion control netting (ENKAMAT) was laid above the site to slow sheet flow over the area. Capturing sediment from the sheet flow, the ENKAMAT provides a stable base for futher plant growth (Photos by the Protect Kahoʻolawe ʻOhana).

Figure 6.22 (*below*). Photograph of successful planting in the gully above the check dam (in background) and on the erosion control netting laid above the headcut control (Photo by Protect Kaho'olawe 'Ohana, 1989).

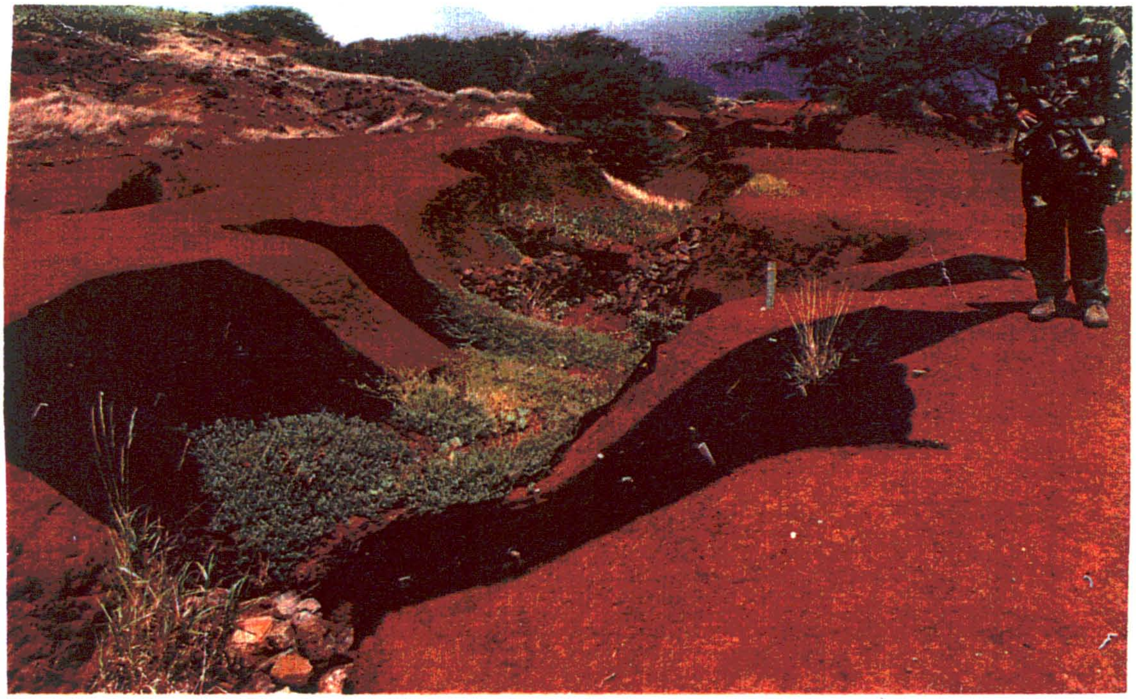


Figure 6.23 (*below*). Photograph of an existing military check dam on Kaho'olawe constructed of tires. These check dams are generally ineffective in controlling soil erosion (Photo by Protect Kaho'olawe 'Ohana, 1988).

Mauka II Study Site

The Mauka II work site selected for demonstration project development is considerably different than the Mauka I site, having steeper slopes and a larger and longer barren area over which water flows (slope lengths between 700-1000 feet). In addition, the gullies on the hardpan are discontinuous gullies, appearing and disappearing, with no uniform depth nor slope relations. There are large areas of the hardpan that are in the rill development stage, exhibiting extreme instability upon prolonged rainfall. A headcut control structure, a check dam and a runoff catchment were constructed at the Mauka II site.

Following the analyses presented for the Mauka I site, similar investigations of gully geometry were undertaken for the hardpan area check dam. Because of the discontinuous nature of the gullies in this region, each segment was analyzed separately and check dam height and spacing relationships developed for each segment. Table 6.6 presents the relevant gully dimensions. Hydrologic analyses for the 1 square mile contributing drainage area of this gully are presented as Table 6.7. The largest flow rate the check dam must be able to accommodate is 20 cfs.

Table 6.6. Gully Dimensions, Mauka II Site
Hakioawa Watershed, Kaho'olawe
(values in feet)

Gully System	Length	Top Width	Bottom Width	Depth	Slope
Mauka II	465	4.03	1.54	2.5	5.8%

Note: Values are averages based upon the analysis of the gully with 25 segments measured.

Table 6.7. Analysis of Runoff for Check Dam Structures
for Mauka II Work Site

Drainage Area	Design Rainfall	Depth of Runoff/in rain	Peak Flow
5 acres	7.5 in	5.9 in	20 cfs
	3.0 in	2.0 in	6.8 cfs

Note: Curve Number = 89, Hydrologic soil group D

The final spacing and height relationships of check dams on the hardpan are presented as Table 6.5. As can be derived from the table, the suggested check dam spacing varies with each reach and is approximately 135 feet for the first segment. The average check dam height is 3 feet. Although several check dams could have been constructed had time allowed, only one check dam was constructed. Figure 6.24 illustrates the hardpan check dam, constructed of loose rock.

Figure 6.24. Photograph of Mauka II check dam completed in January 1989 (Photo by C. Vandemoer, 1989).

The hardpan headcut control structure is shown in Figure 6.25, and is the same design as but larger than the structure at the Mauka I site. This structure was constructed on a headcut in Papakaiki Gulch, however, its headward advance toward the major tributaries of the Hakioawa system make its control necessary for stability in the hardpan region between these two gulches.

As with the Mauka I site, rainstorms during the course of the project permitted a direct evaluation of the soil conservation structures installed. The check dam, following a 3.5 inch storm, deposited over 3 feet of sediment a distance of 47 feet upstream. The sediment behind the check dam was damp upon arrival two weeks after the rainfall event. Over 300 plants were placed in this sediment during March, 1989 and continue to thrive (Figure 6.26).

The headcut control structure suffered heavy damage as result of winter rainstorms and runoff events. The kind of damages suffered to the structure are illustrative of the forces of runoff prevalent on the island, and signal the needed adjustments in headcut construction materials necessary to address the hydrologic conditions prevalent on the hardpan. Briefly, these adjustments include the use of

Figure 6.25. Photographs showing the completed Mauka II headcut control structure. The headcut control is constructed like an inverted filter to slow the water as it enters the gully. Burlap bags are used to slow water at the top of the structure followed by small gravel and increasingly larger grades of rocks (*top*). The headcut is secured by wire and rebar posts at its bottom (*below*). (Photos by the Protect Kaho'olawe 'Ohana, November 1988)

Figure 6.26. Photograph showing the successful capture of soil behind the Mauka II (after only 3 rainfall events) and the subsequent planting of native pohuehue. The photo below shows the plants one month later (April 1989).

larger rock material, the importance of angular rocks used in construction, the need for firm downslope anchoring and for greater upstream streamflow control. In this regard, it is critical that the headwaters of all the gulches and developing gullies be stabilized if effective water control is to be achieved.

Revegetation

Revegetation is a key component of watershed management and restoration. Vegetation holds soil within and around its root system, stabilizing slopes. Vegetation also slows the velocity of water, thereby decreasing its erosion potential. Within a watershed, water transports soil downstream, and the more soil that is transported out of the watershed, the more impoverished existing soils become in relation to their ability to support vegetation growth. Eventually, as the soils are eroded vegetation diminishes or disappears, leaving the watershed in poor condition.

Revegetation efforts at the Mauka I and Mauka II sites were developed to demonstrate the ability of vegetation to slow the velocity of water passing through it and to demonstrate the ability of vegetation to capture soil. In conjunction with check dam activities, the overall revegetation -- soil erosion control approach demonstrates the integrated nature of resources within a watershed, and how the manipulation of one resources (soil, for example) necessarily involves other resources (water and vegetation).

Both the Mauka I and II sites were chosen utilizing a number of factors. First, the contributing watershed area to the site where techniques would be practiced had to be smaller than 10 acres, so as to be able to control the water entering the sites. Second, the sites are both located near the top of the watershed, so as to begin the process of erosion control as far up in the watershed as possible. Finally, the sites were chosen specifically to demonstrate techniques that could be used to stop or arrest gully growth by headcut advancement into the upper portions of the watershed.

At both the Mauka I and II sites, erosion-control netting was used to slow the velocity of water and to trap soil carried by streamflow (Figure 6.21). The objective of this, and many erosion netting approaches, is to create a grassed or vegetated waterway that aids in the control of erosion. Erosion netting breaks the impact of raindrops and spreads the flow of water over a large distance so as to prevent gullying or slope wash from initiating new erosion problems. It is by far the method preferred to control sheet flow and sheet wash, and is considered superior to rough grading as it provides for more direct water control and protects the surface soils from sheet wash erosion. Again, the netting also acts as a trap for soils. Photographs documenting the progress of each site clearly show the dual effects of revegetation and capture of soil by the erosion netting provides a firm foundation for roots and enables the growth and spread of vegetation on an otherwise hard surface.

Summary: Soil Conservation as a Key to Natural and Cultural Resource Management on Kaho'olawe

This chapter has illustrated several techniques by which the complimentary goals of soil and water management are achieved through the construction of check dams and other erosion control structures at selected localities within a watershed. The chief value in the construction of demonstration projects has been to illustrate a procedure through which erosion control measures can be effectively constructed. The procedure involves the examination of a watershed or subwatershed, identification of the primary erosion process, the inventory of the physical system and determination of the hydraulic parameters contributing to soil erosion, and the selective placement and sizing of structures, including adequate bank and channel erosion protection. Other watershed restoration tools, including erosion netting and revegetation strategies, compliment structural or engineering activities.

To achieve the many goals for resource use and management of Kaho'olawe, an interdisciplinary approach is the necessary tool through which the skills and knowledge of the scientific community can be brought to bear on solutions to the problems of Kaho'olawe's fragile environment. By combining the tools and techniques of hydrology, soil physics, hydraulics, conservation, botany, agronomy and plant physiology, the results of the Kaho'olawe project work demonstrate the viability of such an approach to the management of island resources and the restoration of critically-eroding watersheds.

For Kaho'olawe, it is impossible to separate land from water, water and land from vegetation, and water and vegetation management from archaeological and cultural resource management. The demonstrated link among all these factors make the leap toward an interdisciplinary perspective necessary.

Notes to Chapter 6

[1]U.S.Department of Agriculture, Soil Conservation Service, Erosion and Sediment Control Guide for Hawaii,1981.

[2] Rill erosion is the process in which numerous small channels only several inches deep are formed. Rill erosion is described in greater detail later in this chapter. Sheet erosion is the removal of a fairly uniform layer of soil from the land surface by runoff water.

[3]The combined LS factor is used by the U.S. Soil Conservation Service in the USLE to describe the effect on soil loss of the combination of slope length and gradient.

[4] Hydraulics describes predictable channel shape, size, slope, etc... which enable use of hydraulic equations that predict hydrologic (i.e. volume and rate of runoff) responses.

[5]For an excellent discussion of this process see L.B. Leopold, G. Wolman and J.P. Miller, Fluvial Processes in Geomorphology, 1963.

[6]B.H. Heede, Gully Development and Control: The Status of Our Knowledge, 1979.

SECTION FOUR

Water Demands, Sources and Management

Introduction

Previous sections of this report have described the physical setting, condition and characteristics of surface and ground water resources of Kaho'olawe. The link between land and water management has been demonstrated by calculating surface runoff and the quantity of soil loss as a result of this runoff and by the construction of structures that have captured soil after runoff events. The next phase of the investigation involved the determination of the water resource demands posed by the several land use plans that have been developed for Kaho'olawe. In addition, the water resource demands associated with activities designed to manage and control soil erosion, and water demands associated with the stabilization of archaeological sites were estimated. Once the demands were quantified, the quantity of water available from Kaho'olawe to meet these needs was assessed. Additional sources that can be tapped to meet demand were also investigated.

To demonstrate the feasibility of water development on Kaho'olawe, several demonstration projects were constructed. Three rainfall harvesting structures, with a total capacity of 2,920 gallons were constructed. A runoff catchment was also constructed. The successful capture of approximately 1,000 gallons of water during the period from November 1988 to February 1989 demonstrates the feasibility of rainfall harvesting to serve as a source of water for revegetation efforts.

This section provides a summary of the many water resource demands on Kaho'olawe and the quantity of water potentially available from indigenous island resources.

CHAPTER 7

Water Demands and Water Sources

Water Demand

The water demand on Kaho'olawe originates from three major sources:

1. Revegetation/conservation requirements,

2. Requirements needed to fulfill the objectives of the Maui County Community Plan for Kaho'olawe, and

3. Water demands for present military uses of water on Kaho'olawe.

These demands are discussed below, including the assumptions used to quantify demand.

Island Soil & Water Conservation Programs

The urgency of the conservation work on Kaho'olawe cannot be understated. As discussed earlier, the island's environment is at a threshold situation due to tremendous soil loss from uncontrolled water runoff down unvegetated slopes and increasing gully expansion. Soil loss estimates indicate Kaho'olawe has one of the highest erosion rates in the United States. As noted earlier, northeastern watersheds on the island have soil loss rates estimated as high as 127,000 tons annually.

In the past few years of research, it has become clear that the effective management of the water resource on Kaho'olawe is key to the revegetation of the island and stabilization of Kaho'olawe's soil and archaeological resources. Water requirements for conservation activities will focus primarily on revegetation efforts, which require extensive water use.

Revegetation Programs

Revegetation and rehabilitation of Kaho'olàwe's soil, vegetation and water environment has been proposed for many years by the State and Territory of Hawai'i, the County of Maui, and many individuals and community organizations. However, attempts to develop and implement a long-term revegetation program have largely failed partly due to the complex nature of the problem. Past planting plans have focused primarily on the identification of appropriate species for the island's denuded environment; and more recently, the identification of species which meet the native revegetation criteria raised by the Protect Kaho'olawe 'Ohana and described in the Maui County Community Plan. Little effort has been made toward the identification of water resource requirements for such ventures.

Two major planting efforts undertaken by the State (Whitesell et al., 1971, 1972) and the Native Hawaiian Plant Society (in 1983, 1985), as well as field observations conducted as a part of the Kaho'olawe Water Study have provided valuable information from which to estimate the kinds of species appropriate for Kaho'olawe and the water requirements for establishing a ground cover of these species.

Water demand for revegetation is necessary for plant acclimatization to Kaho'olawe's harsh environment. Normally planting occurs during the rainy season to take advantage of available rainfall, however, sufficient watering is not assured therefore, the development of a water source is important for plant survival.

Design Criteria. In order to develop estimates of water demand, some assumptions must be made regarding the type and extent of planting projects, as well as the type of plants used in the effort. There are obviously many levels of analysis possible here, however, key design criteria used for this study are presented and discussed below.

1. *Land Base for Planting Efforts.* As a first approximation, the land base considered for planting in this report is that deemed in critical need of vegetation cover. As discussed in previous sections of this report, these lands generate considerable quantities of runoff and are presently threatened by increasing rill and gully development. Moreover, these lands presently contain a high density of archaeological sites that are similarly threatened by soil erosion. The land base for planting identified in this report then, is approximately 10,000 acres, located on the eastern third of the island in the headwaters of several major gulches. Figure 7.1 shows suggested planting areas in critical watersheds - primarily areas with a barren surface and vulnerable to sheet and wind erosion.

2. *Climatic Zones as Guides to Vegetation Types.* Because of the inherently dry conditions on Kaho'olawe, vegetation types must be selected that take advantage of the available moisture, which may vary with elevation, rainfall distribution, and other microclimatic factors, such as watershed orientation and the existence of stands of other vegetation that provide a wind break and place for moisture to collect.

   Climatic zones were proposed on the basis of an estimated rainfall distribution for Kaho'olawe, field observations of soils, plant types and weathering processes at different altitudes (Table 7.1). However, it is not clear whether these variations in climatic conditions are significant enough to define separate vegetation zones.[1] More research into this vital component of watershed planning should be undertaken.

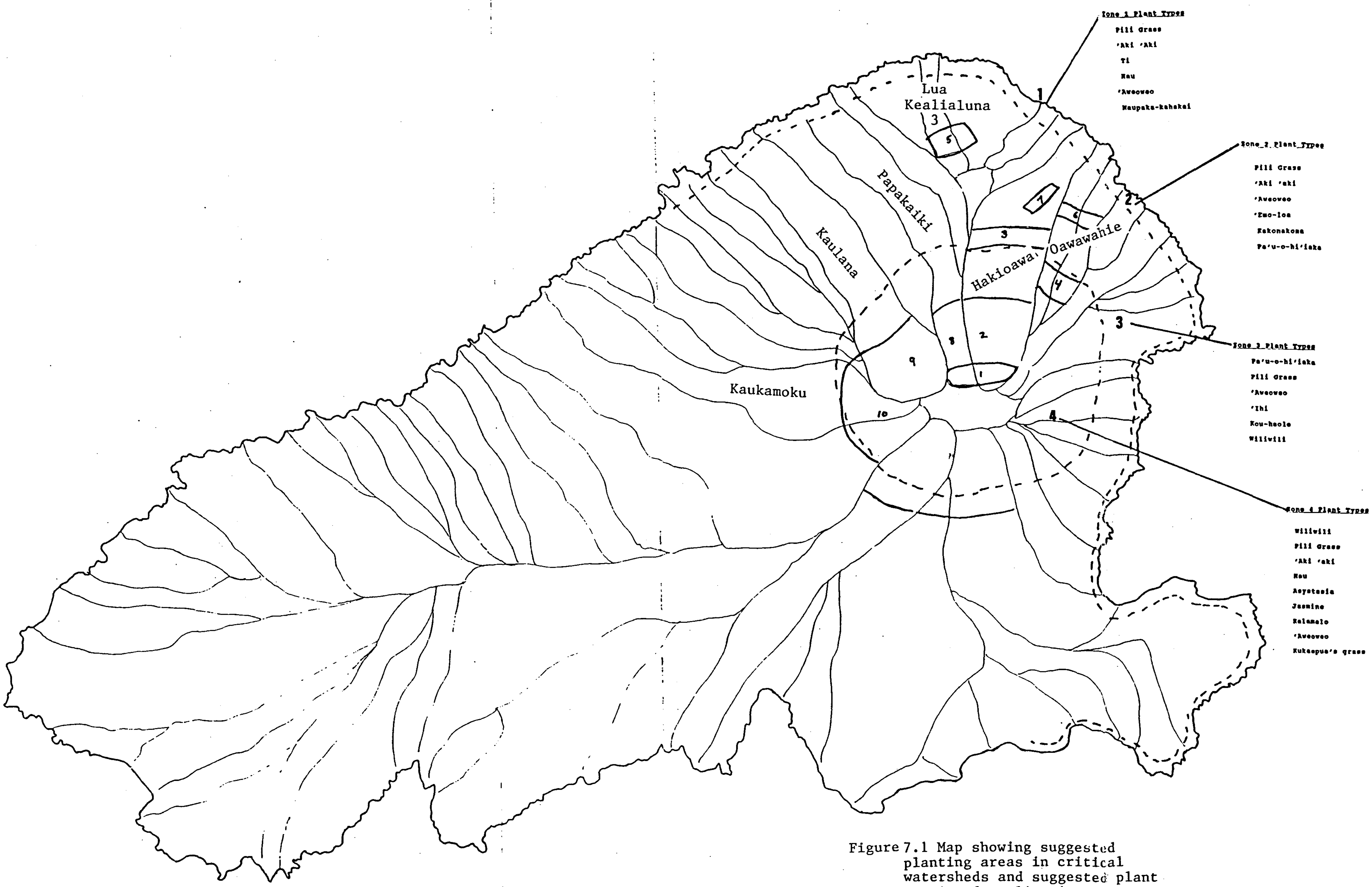


Figure 7.1 Map showing suggested planting areas in critical watersheds and suggested plant species for climatic zones

Table 7.1. Supporting Data for Climatic Zones, Kaho'olawe Island

Zone	Altitude	Water Supply *Estimates
1	0'-10'	8-10
2	10'-300'	10-14
3	300'-1,000'	15-18
4	1,000'-1,400'	18-25

**In thousands of gallons*

3. *Selection of Plant Species.* Selection of plant type and species for revegetation is defined by the following criteria: 1) plant types must be able to withstand generally dry conditions; 2) plant types must be able to withstand certain depths and velocities of runoff, and must be able to act to slow water velocities; and 3) the plant species must be native to the Hawaiian ecology, with no inclusion of exotics. In general, a mixture of species is desirable as it produces greater variety and provides an opportunity for experimentation. A list of native plant species used in both the Native Hawaiian Plant Society and Protect Kaho'olawe 'Ohana planting trials is presented in Table 7.2.

4. *Revegetation Planting Pattern.* There are many possible patterns for the revegetation effort on Kaho'olawe. However, it is imperative that revegetation efforts be used to assist the control of soil erosion on Kaho'olawe; without a stable soil base it will be more difficult to establish a vegetation cover. In view of these needs, the pattern adopted for the purposes of this estimate of water needs is a strip-cropping or terracing pattern planted on the contour, or parallel to slope contours. Figure 7.2 illustrates the pattern for a selected planting area in the headwaters of Hakioawa gulch. Row length varies between 100 and 300 feet; row width is 50 feet. For a 400 foot slope, five strip rows are required for rows spaced 42 feet apart. A mixture of species is planted at a density of approximately one plant per two-foot square for individual plants, with grasses intermixed throughout. The area represented in Figure 7.2 is approximately 200 acres.

   It is important to note that revegetation as defined by this planting methodology, does not mean complete vegetative cover of the entire land surface. Instead, plantings are located in strategic areas in the watershed to prevent further soil loss.

Table 7.2. Native Plant List for Kaho'olawe Island

Scientific Name	Hawaiian/Common Name	Status[1]
Agavaceae		
Pleomele aurea	hala-pepe	E
Aizoaceae		
Sesuvium portulacastrum	'akulikuli	I
Boraginaceae		
Heliotropium anomalum	hinahina	I
(var. Argenteum)		w/E var.
Chenopodiaceae		
Chenopodium oahuense	'aheahea, 'aweoweo	E
Asteraceae (Compositae)		
Artemisia australis	hinahina	E
Lipochaeta lavarum	nehe	E
Convolvulaceae		
Bonamia menziesii	---	E
Ipomoea brasiliensis	pohuehue	I
Jacquemontia ovalifolia	pa'u o Hi'iaka	E
Cyperaceae		
Mariscus javanicus	'ahu'awa	I
Ebenaceae		
Diospyros sandwicensis	lama	E
Euphorbiaceae		
Aleurites moluccana	kukui	P
Chamaesyce celastroides (formerly *Euphorbia*)	'akoko	E
Fabaceae (subfam. Caesalpinioideae)		
Senna gaudichaudii (formerly *Cassia*)	Kolomona	I

[1] Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction

Table 7.2 (Continued)

Scientific Name	Hawaiian/Common Name	Status
Fabaceae (subfam. Mimosoideae)		
Acacia Koa	koa	E
Acacia koaia	koai'e	E
Fabaceae (subfam. Papilionalae)		
Erythrina sandwicensis	wiliwili	I
Sophora chrysophylla	mamane	E
Goodeniaceae		
Scaevola coriacea	dwarf napaka	E
Malvaceae		
Abutilon menziesii	ko'oloa 'ula	E
Gossypium Tomentosum	ma'o	E
Hibiscus brackenridgei	ma'o hau hele	E
Malvaceae (continued)		
Hibiscus tiliaceous	hau	I
Sida fallax	'ilima papa	I
Thespesia populea	milo	I
Myoporaceae		
Myoporum sandwicense	naio	I
Papaveraceae		
Argemone glauca	pua-kala	E
Poaceae (Gramineae)		
Eragrostis variabilis	'emoloa, kalamalo	E
Ischaemum byrone	hilo ischaemum	E
Portulacaceae		
Portulaca molokiniensis	'ihi	E

1 Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction

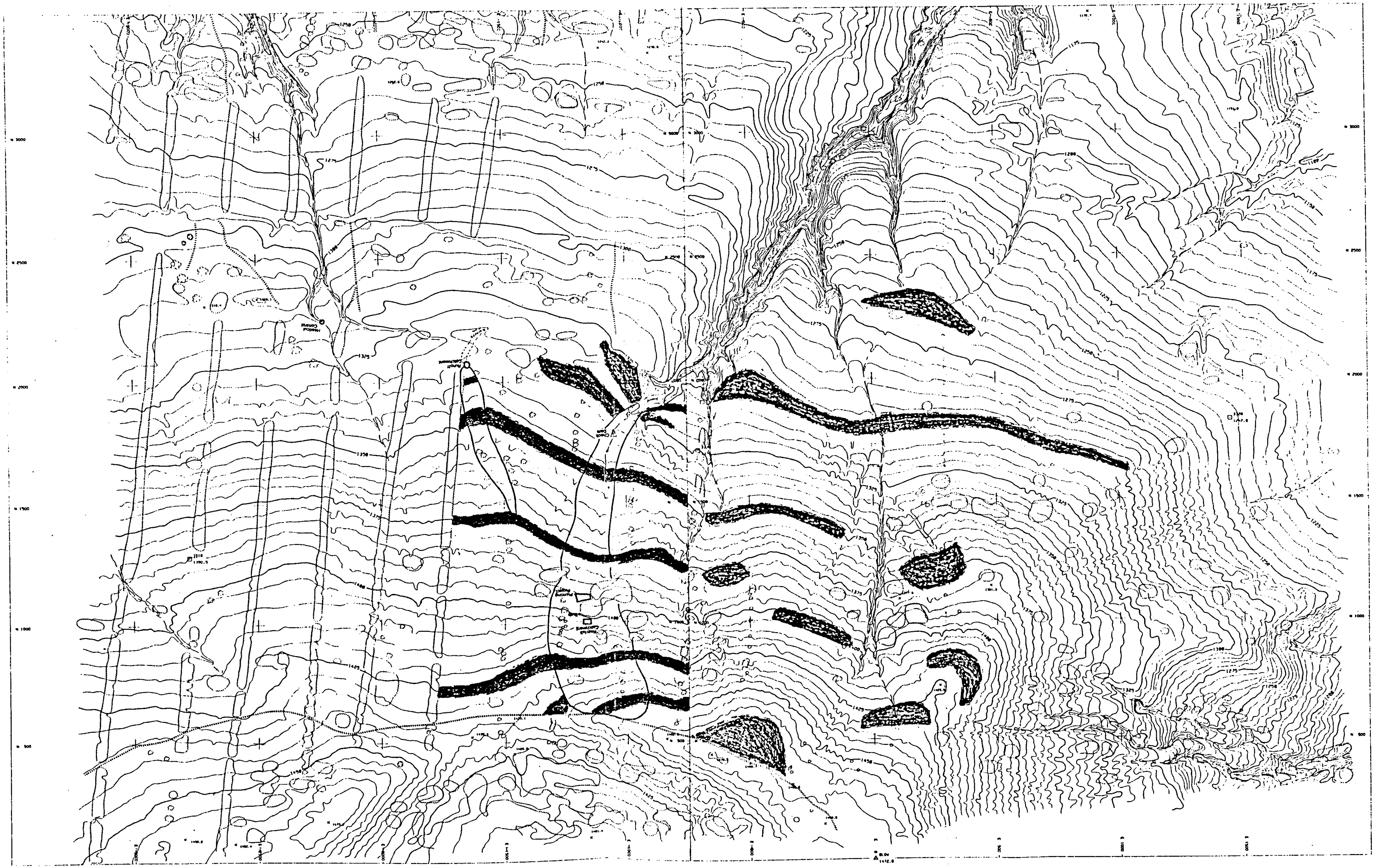
Table 7.2 (Continued)

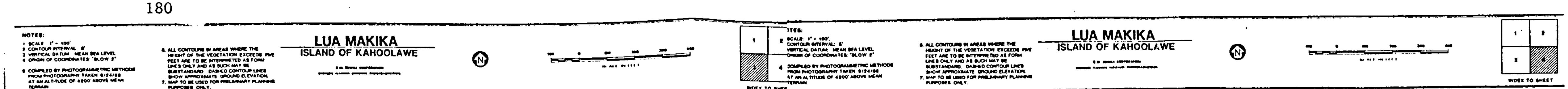
Scientific Name	Hawaiian/Common Name	Status
Rhamnaceae		
Alphitonia ponderosa	kauwila	E
Colubrina asiatica	'anapanapa	I
Rosaceae		
Osteomeles anthyllidifolia	'ulei	I
Rubiaceae		
Canthium odoratum	alahe'e, walahe'e	I
Morinda citrifolia	oni	P
Santalaceae		
Santalum ellipticum	'iliahi a lo'e	E
Sapindaceae		
Dodonaea viscosa	'a'ali'i	I
Verbenaceae		
Vitex rotundifolia	pohinahina	I

[1]Phytogeographic Status: I=indigenous; E=endemic; P=polynesian introduction. Endemic to the Hawaiian islands i.e. occurring naturally nowhere else in the world. Indigenous refers to native to the Hawaiian islands, but also occurring naturally elsewhere (without aid of humans). Polylnesian introduction includes those plants brought by the Polynesian immigrants in pre-haole times to the Islands.

Nomenclature based on taxonomy in *Manual of the Floweringq Plants of Hawai'i,* W.L. Wagner, D.R. Herbst, and S.H. Sohmer, Honolulu, Hawai'i: Bishop Museum Press and University of Hawaii Press, 1990.

Figure 7.2 Selected planting pattern
Hakioawa Gulch headwaters





5. *Water Use and Timing of Water Delivery.* Water requirements for each species were estimated from related data available from the State of Hawai'i, the University of Hawai'i Agriculture Extension Service, and discussions with persons knowledgeable of native species and their water use requirements. Additional information was obtained from the records of vegetation trials on Kaho'olawe maintained by project personnel.

Trial plantings on Kaho'olawe have demonstrated that the most critical time in a plant's life is the first three to four weeks, when water must be supplied in sufficient quantities to enable the plant to survive. Once established, these plants should be able to take advantage of available rainfall. Data indicate that for the species listed in Table 7.2, 1 quart of water per plant per week for the first four weeks is the minimum quantity desirable. Optional waterings through the plants' first summer were also suggested to prevent potential die-off.

6. *Phased Implementation of Revegetation.* The phased implementation of revegetation programs is a major criteria involved in developing annual water requirements of plants. For the purposes of this report, we contemplate the revegetation of 2,500 acres (3.9 square miles) annually to provide a minimum of stabilization for the critical hardpan area. Once the first 10,000 acres are treated, additional work for complete environmental restoration may continue in the same area.

Other Soil Conservation Strategies.

As emphasized in the previous chapter, soil conservation requires an integrated approach combining several measures to achieve stabilization of the soil base. In addition to terracing mentioned above, conservation measures include construction of check dams and headcut controls, installation of erosion netting, construction of water catchments and diversion structures. However, the water requirements for the construction, installation and maintenance of these activities is relatively small (related primarily to consumption for workers), the work is fairly extensive (see Chapter 8).

Annual water demand for soil and water conservation efforts is summarized in Table 7.3 as a part of the water demand for associated activities also identified in the Kaho'olawe Community Plan. Given the criteria developed, the estimated annual water need for conservation efforts is approximately 350,000 gallons, with much of the demand concentrated in revegetation projects. Other water demands for implementation of the Community Plan objectives are discussed in the following section.

Kaho'olawe Community Plan

In June, 1982, the Kaho'olawe Community Plan was adopted pursuant to the Charter of the County of Maui and the Maui General Plan. The plan sets forth the broad objectives and policies for the long-range development.of the county, including the island of Kaho'olawe, and specifies the desired sequence, pattern and characteristics of development on the island. The plan also identifies a proposed pattern, distribution and intensity of land use practices on Kaho'olawe for a 15-20 year framework (EDAW, 1982). Because the Kaho'olawe Community Plan is so specific, it is possible to use the plan to develop estimates of water demands, given the scope and objectives of planned community activities.

The Kaho'olawe Community Plan specifies a number of island activities, all of which have some demand for water. In general, the plan calls for the development of Kaho'olawe as a cultural park, with temporary and permanent base camps for the purpose of conducting educational, religious, cultural and scientific activities. In addition to specifying overall targets, the plan includes a number of specific provisions, all of which will add to the demand for water on Kaho'olawe. The major provisions include the following:

- Designation of an increasing portion of the land base (over 15 years) as a Cultural Use Area for the purpose of conducting educational, cultural, scientific or religious activities;
- Development and maintenance of hiking trails for visitor safety and to protect archaeological sites;
- Development of a fire suppression program to protect vegetation;
- The development of base camps for accommodating up to 50 people; and
- Archaeological site stabilization and maintenance.

As mentioned earlier, the Kaho'olawe Community Plan does call for continued soil erosion control activities, including revegetation, installation of wind breaks, goat eradication, construction of check dams, and other activities. Due to the importance soil and water conservation, water requirements for these activities were treated separately in the prior section.

The Community Plan also calls for a comprehensive water study, of which this project is an outcome. Moreover, the development of cultural resource management and soil erosion control activities and strategies are specified in the Consent Decree, and were agreed to by the U.S. Navy.

Designation of Land Use Areas. The kind of activities that go on in an area designated for cultural use determine the water demand. As originally envisioned, the Community Plan identified a variety of activities in the cultural use area, for small numbers of people. If those activities are educational, then water needs are manifested by individual water requirements for as long as the educational activity takes place. If the activities are scientific, water demand depends on the type of scientific work produced: for example, hiking versus construction. Cultural and religious activities imply light use of the region accompanied by water demands for individual consumption. Hence, water demands are estimated over a period of time for certain numbers of individuals.

Development of Hiking Trails. Two phases of water demand accompany this planned activity. First is construction of trails, involving water needs of working individuals and any additional water needs for concrete work. The second need is the strategic placement of fresh drinking water for eventual users of the trail out for a 6 or 7 hour hike on Kaho'olawe. Figure 7.3 presents a map of suggested locations for drinking water sources. The locations were based on the network of trails outlined in the Kaho'olawe Community Plan.

Development of a Fire Suppression Program. There are three important factors involved in the development of a fire control program: quantity, location and pressure. Regarding the quantity of water resources needed for fire protection is presently needed for all major vegetation zones on Kaho'olawe. However, the vegetation in and surrounding the present target area is at greater risk and must therefore be a priority for fire control. Therefore, the estimation of water needs for fire suppression was developed for approximately 8,000 acres in the central one-third of the island.

Fire protection is also needed for each of the present and planned future base camps. Water needs for this component were estimated on the basis of the size of the camp and the vegetation fire hazard. Fire protection water needs varied from 1,000-5,000 gallons per camp site.

Development of Additional Base Camps. Currently the Protect Kaho‘olawe ‘Ohana maintains a permanent base camp at Hakioawa capable of supporting 30-80 people for short periods of time (3-10 days). Additional base camps, supporting 30-50 people for similar time periods are identified in the Community Plan for coastal bays like Kuhe‘eia, Ahupu, Honokoa, and Keanakeiki. This plan calls for the development of 2 base camps near the island's summit to facilitate work in the eroded hardpan area.

Water is needed for drinking, cooking and washing; fire protection was discussed above. Small-scale planting projects in each of the base camps may also require water, in amounts specified in the revegetation section above. Based on the extensive experience of the 'Ohana in coordinating and conducting public access to Kaho'olawe for 50 or more people in the last several years, the water needs of temporary and permanent base camps can be estimated.

The 'Ohana requires a minimum of five gallons for each person for a three day visit to the island, roughly 1.7 gallons of water a day per person. Water use is restricted with baths taken in the ocean. Additional water is brought normally to support kitchen and cooking requirements. For 50 people, a minimum of 250 gallons of water are needed over a three day period. The 'Ohana work crew for the water study averaged between 4 and 6 gallons per person per day. For 6 individuals, 4 days, this amounts to between 96 and 144 gallons. For 50 people consuming 6 gallons per person per day, 1,200 gallons of water are needed over a 4 day period.

Logistically, water presents a major problem for 'Ohana visits. Since there are no docking facilities on the island, the water must be carried from the boat to shore by Zodiac, requiring numerous trips. Development of an island water supply would reduce logistical requirements and provide visitors with greater flexibility with water use. An additional five gallons of water per person per day could be added to accommodate limited freshwater showers.

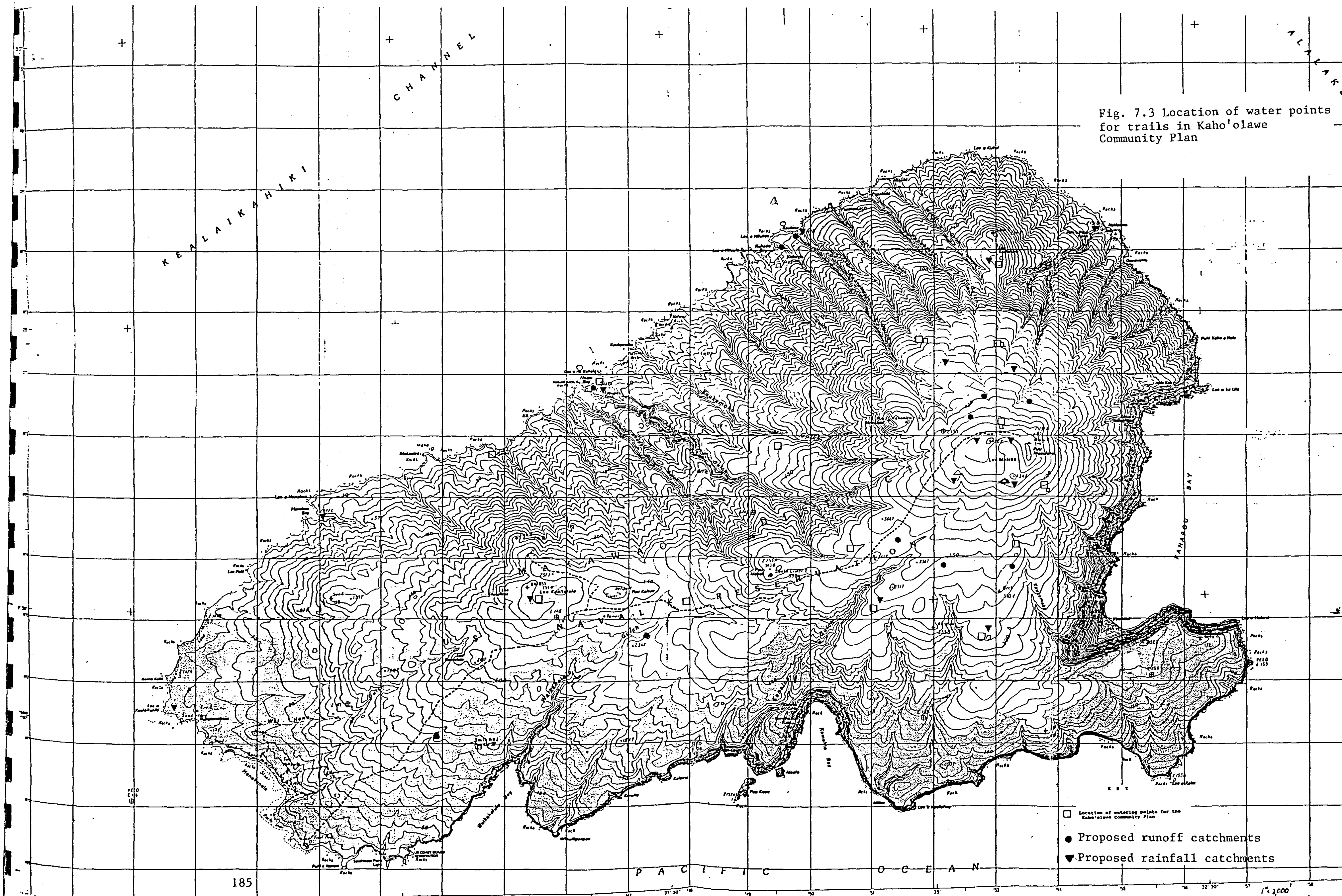


Fig. 7.3 Location of water points for trails in Kaho'olawe Community Plan

Given this background information, the annual water needs associated with the activities of the Kaho'olawe Community Plan are tabulated in Table 7.3.

Table 7.3. Annual Water Needs Associated with the Activities of the Kaho'olawe Community Plan

Water Use Activity	Location	Annual Water Needs
Island Soil and Water Conservation*	10,000 acres, eastern third of Kaho'olawe	350,000 gallons
Base Camp Development	Four new locations	90,000 gallons
Cultural Use/Hiking Trails	Various locations (See Figure 7.3)	1,000 gallons
Fire Suppression	Base camps & target range	54,000 gallons
Educational/Scientific	Variable sites	1,500 gallons
	TOTAL:	**496,500 gallons**

* Water demand is primarily for revegetation, but also includes smaller requirements for construction of check dams, headcut controls, terraces, water catchment and diversion, and installation of erosion netting. A portion of conservation requirements for personnel are also included under base camp development and education/scientific activities.

Military Water Use

Use of water by the U.S. Navy on Kaho'olawe is primarily for drinking water, showers, and cooking for 100-150 people regularly on island for a 10-day period and for 10 others remaining on island at other times. Water use information supplied by the Navy is the most recent available data and constitutes <u>estimates</u> of actual use and cost.

At present, the Navy has two 10,000 gallon tanks on Kaho'olawe. While one tank is used in reserve, the remaining tank is filled with potable water every two weeks imported from O'ahu. In addition, the Navy uses eight "water buffaloes", or 400 gallon wheel-mounted tanks filled with non-potable water for showers; these are also filled every two weeks. Total use is reported by the Navy to be 120,000 gallons annually.[2]

Summary of Water Needs

A summary of the major water needs of Kaho'olawe given three broad categories of activity is presented as Table 7.4. As derived from the table, the annual water need for Kaho'olawe is approximately 616,500 gallons. This figure should probably be increased by 25%, owing to the possibility of additional planting projects and domestic demands as the years go on. This brings the **total annual need to approximately 770,625 gallons.** This amount is extremely small compared to water demand of neighboring islands.

Table 7.4. Summary of Total Water Resource Needs, Kaho'olawe, Hawai'i, 1989

Water Use Activity	User	Annual Water Need
Island Soil & Water Conservation	All	350,000 gallons
Kaho'olawe Community Plan*	Community	96,500 gallons
Military Water Use**	Military	170,000 gallons
		TOTAL: 616,500 gallons

Note: * The Community Plan includes 1,000 gallons for cultural use and hiking and 1,500 gallons for educational and scientific uses and 4,000 gallons for fire suppression.
** The Military Water Use includes 50,000 gallons for fire suppression

Potential Water Sources

The previous section estimated the annual water needs for selected uses of the island of Kaho'olawe. If present and future activities are to continue, and if resource conservation and archaeological site stabilization is to be effective, the demand for water must be met. This section delineates the possible sources of water to meet demand, building upon earlier chapters discussing the surface and ground water resource. The costs of water resource development are estimated in the final chapter as a part of the development plan proposed for Kaho'olawe.

Ground Water Resource Development

The location and occurrence of ground water, as delineated in this study, was discussed as the subject of Chapter 5. As disclosed, there is a body of ground water on Kaho'olawe whose lateral extent appears to cover approximately 15,000 acres; the freshwater head in this aquifer is large, with the greatest thickness of the ground water body in the range of 600-700 feet. While it is expected that this feature is dike-impounded water, further research, in the form of a drilling program, is necessary for absolute determination of the occurrence of ground water in this region.

Given, however, a rough approximation of the aquifer outline and thickness of fresh water, a range of possible ground water quantities can be estimated under different assumptions of porosity of the unit and the size of dike-impounded compartments. These values are tabulated in Table 7.5. The locations in the table can be found on the map in Figure 5.12 in Chapter 5. It is important to recognize that the figures in Table 7.5 are estimates only and include a wide range of assumptions.

Table 7.5. Estimates of the Volume of Ground Water for the Dike-Impounded Feature on Kaho'olawe Under Different Assumptions of Porosity.*

Area	Average Thickness of Freshwater**	Quantity of Water for Selected Porosity*** (Values in acre-feet)		
		5%	10%	20%
1. 1,405 acres	574 feet	40,323	80,647	161,294
2. 491 acres	328 feet	8,052	16,104	32,209
3. 1,332 acres	150 feet	9,990	19,980	39,960
4. 1,500	100 feet	7,500	15,000	30,000
Totals:		**65,865**	**131,731**	**263,463**

* One acre foot equals approximately 325,900 gallons of water.

** The areas in the table were determined by examining the contours of the thickness of the dike zone (see Figure 5.12). The area between the contours was planimetered to measure area. This represented the thickness of the dike-impounded feature holding ground water.

*** The quantity of water was determined using the following formulas:
Volume = Area x Thickness and Volume x Porosity = Space Occupied by Water.

The other part of the formula, in addition to total quantities, is the potential yield from the formation in gallons per minute. As mentioned in Chapter 6, it is expected that the aquifer at depth is very fine-grained because of Kaho'olawe's geologic history and known rock types on the island. However, the fracturing and rift zones that accompanied Kaho'olawe's formation may actually act to increase yield. Given the wide variety of possible conditions, we can only estimate the yield of ground water assuming different pumping rates and specific capacities. These values are shown in Table 7.6.

Table 7.6. Quantities of Water Derived under Different Yield Assumptions, Kaho'olawe

Pumping Rate (gallons per minute)	**Quantity of Water Derived** (gallons per day)	**Annual Yield** (gallons)
2	2,880	1,051,200
10	14,400	5,256,000
20	28,800	10,512,000

Note: Actual yield may be much lower with varying specific capacities.

There are major uncertainties with ground water as a potential source of water for Kaho'olawe activities. First, the actual yield and quantity of recoverable ground water on Kaho'olawe is unknown, and awaits further investigation. Second, the quality of water is an unknown factor, and most definitely will affect agricultural and domestic uses of water. Saline sensitive soils on Kaho'olawe would not tolerate an additional source of salinity. It is suspected that much of Kaho'olawe's ground water has a high dissolved solids content and is on the brackish side; this is a likely result from alteration minerals in the subsurface, such as clays, which impart salinity to ground water. Finally, low recharge reduces the quantity of fresh water replenishing the aquifer.

However, if further investigation of ground water is undertaken, and even small yields are proven, it is apparent from Table 7.6 that the development and storage of sizable quantities of water is possible. Ground water forms a virtual "gold mine" for badly-needed revegetation efforts.

Basal ground water development would consist of both short term and long term components. First, in the short term, removal of kiawe trees immediately surrounding each dug well might improve both the quality of water and the quantity of water remaining after a recharge event. In the long run, any encouragement of recharge in the drainage area of the well--such as check dams to retain moisture, improvement of infiltration capacity of soils, and small runoff catchments--would improve both the quality and quantity of basal ground water.

Surface Water Development

As indicated in Chapter 4, a substantial quantity of water runs off Kaho'olawe after every rainstorm. The estimated annual quantity of runoff for all of Kaho'olawe is approximately 41,000 acre feet (13.3 billion gallons). Given these large values, it is possible to consider the development of surface water as a means of meeting the water needs specified earlier in this chapter.

On Kaho'olawe, the primary source of water for island residents from 1920-1950 was surface water, diverted from gully flows after each rain storm. However, as environmental conditions changed the harvesting structures filled with sediment and water quality deteriorated. Indeed, there continue to be problems with harvesting surface water at this time. Major problems include the "flashy" nature of stream flow, flooding potential, the high sediment content of stream flow, and finding suitable localities where surface water development will not negatively impact other resources. Large-scale dam development would be too risky at this point, considering the paucity of hydrologic data. Nevertheless, techniques exist and have been demonstrated on Kaho'olawe that can effectively take advantage of surface water flow without the construction of large dams.

To demonstrate the feasibility of developing runoff catchments the Kaho'olawe Water Study personnel constructed a runoff catchment on the hardpan area. Figure 7.5 demonstrates the location of the catchment, while Figures 7.6 and 7.7 show photographs of the completed structure. Note that runoff has simply been channeled into an old bomb crater. The contributing area is .1 acre, and the catchment is expected to harvest approximately 100 acre feet of water annually. The project was designed to demonstrate the feasibility of developing small runoff catchments.

A series of storms occurred shortly after the construction of the runoff catchment. Although no standing water was remaining in the crater when the site was visited 1 month after the storms, runoff was captured because the sediment content of the bottom of the crater was increased by .5 feet. The deposition in the 13-foot diameter crater amounted to approximately 66 cubic feet. (see Figure 7.6)

The high sediment content of Kaho'olawe runoff was again demonstrated by the runoff catchment, and illustrates that soil erosion in the headwater areas must be controlled if runoff is to be used as a viable source of water.

If the sediment problem could be reconciled either through soil erosion control or through the use of a series of filters, the quantity of water potentially available through the development of runoff catchments can be estimated using the methods outlined in Chapter 4. Table 7.7 tabulates runoff amounts from selected size watersheds. As derived from the table, surface water runoff could offer excellent potential for obtaining water to meet Kaho'olawe's water demands.

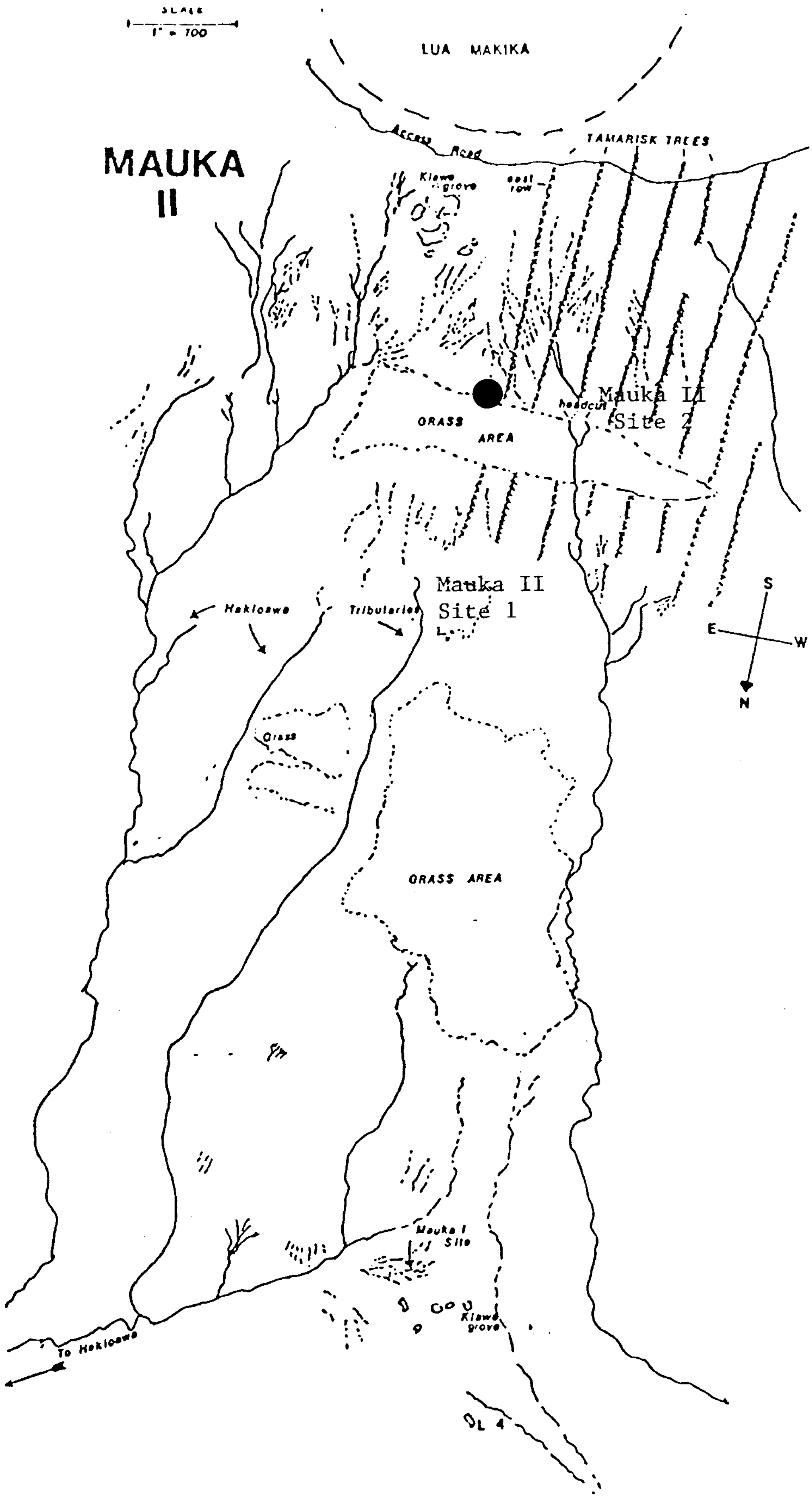


Figure 7.4. Map of the Mauka I and II work sites, locating the runoff and rainfall catchments.

Figure 7.5 (*above*). Photograph of completed Mauka II runoff catchment. The bomb crater is in the foreground (with haole-koa plants) and the cement lined diversion trough leads from the tamarisk treeline, capturing water from the treeline and the subwatershed to the left of the photo. If lined, the catchment could harvest approximately 100 acre feet (32,585,100 gallons) annually (Photo by C. Vandemoer, 1989).

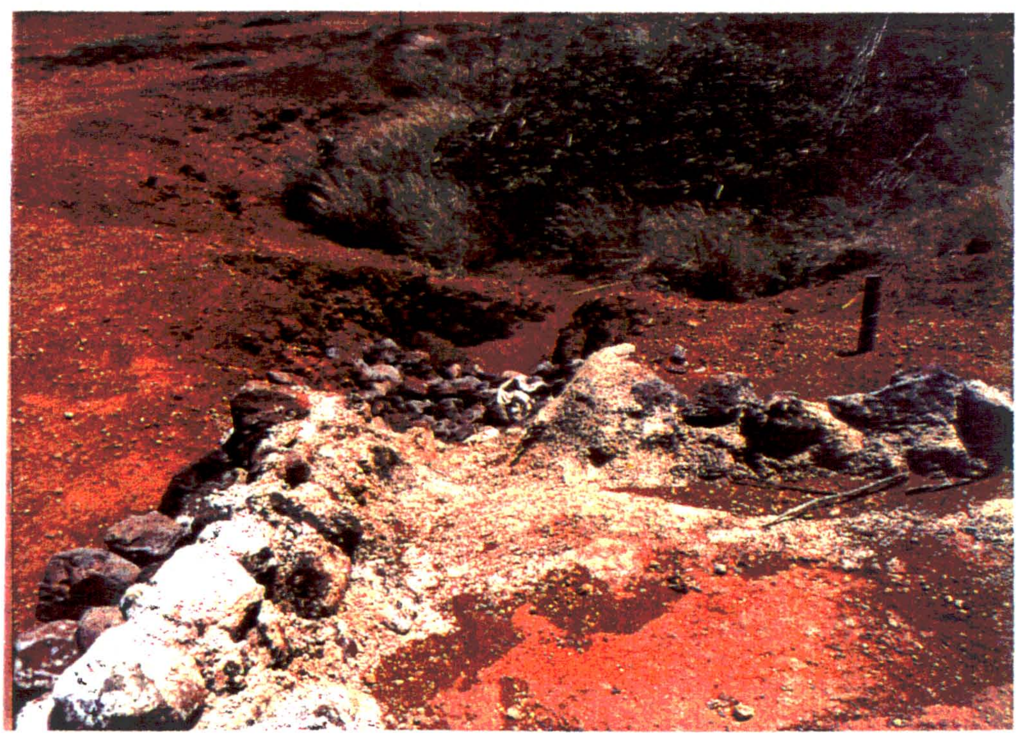


Figure 7.6 (*above*). Photograph of the catchment 1 month after completion. Although no standing water was remaining in the crater, the crater bottom was increased by. 5 feet, evidence of the capture of sediment-rich runoff. The deposition in the 13-foot diameter crater amounted to approximately 66 cubic feet.

Table 7.7. Potential Quantities of Water Derived from the Development of Small Surface Water Catchments on Kaho'olawe[1]

Size of Contributing Watershed	Quantity of Water Harvested for Different Quantities of Runoff (values in acre-feet)		
	3.37"	5.2"	6.22"
5 acre	1.4	2.17	2.59
10 acre	2.8	4.3	5.18
15 acre	4.2	6.5	7.8
20 acre	5.6	8.7	10.4
25 acre	7.0	10.8	12.9
50 acre	14.0	21.6	25.9
100 acre	28.1	43.3	51.8
200 acre	56.1	86.6	103.6

Note: One acre foot equals approximately 325,900 gallons of water.

[1] Runoff values calculated according to the methods presented in Chapter 4 and are based on the 5, 10 and 25 year storm and runoff amounts. Depth of runoff determined for each storm. Curve Number = 85, moderate slopes. Evaporation demand is not factored into this analysis.

Rainfall Harvesting

The capture or harvest of rainfall is another way in which residents of Kaho'olawe obtained water for domestic purposes. Stearns (1939) documented several roof catchments on Kaho'olawe with cistern storage capacities in excess of 50,000 gallons. Although the quantity of annual rainfall is low, many individuals in Hawai'i and elsewhere in semi-arid regions effectively use rain water for a variety of purposes.

To demonstrate the possibility of harvesting rainfall, the Kaho'olawe Water Study constructed three rainwater harvesting structures during the course of the project at both study areas: Mauka I and II (see Figure 7.4). An additional catchment was constructed at the 'Ohana's basecamp at Hakiǫawa Bay. The catchment surface for each structure measured 190 square feet. Figures 7.7 and 7.8 show two of the harvesting structures as they were constructed for 220 gallons, while the Mauka I and Mauka II sites have capacities of 1,200 and 1,500 gallons respectively.

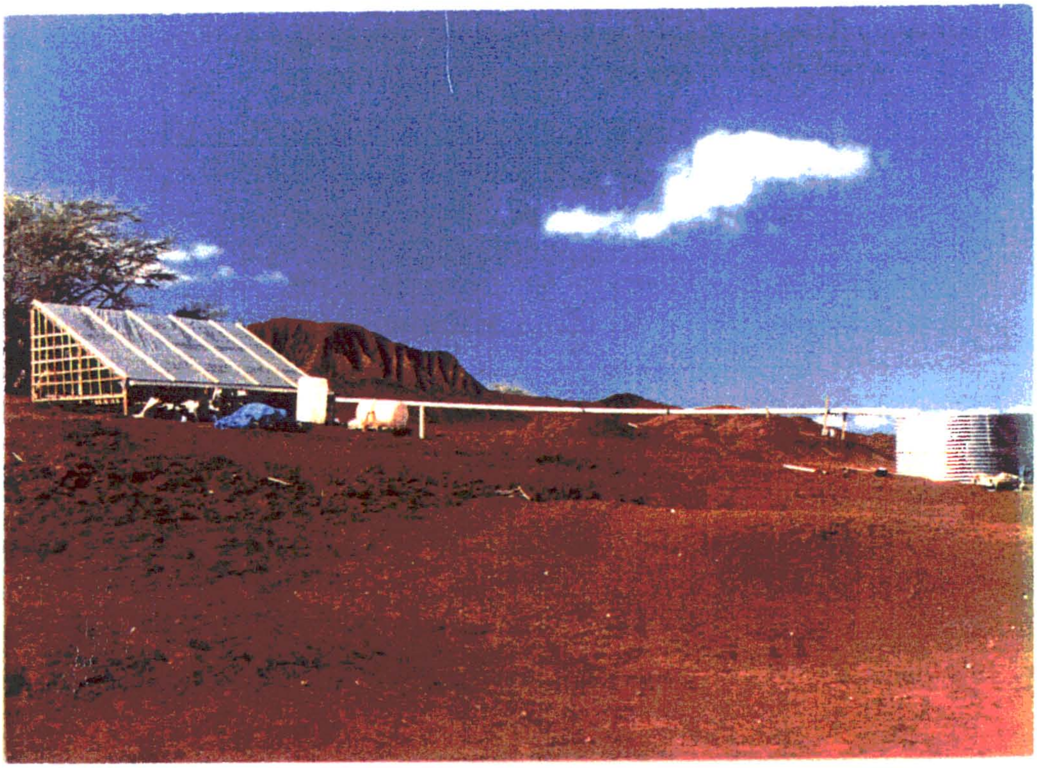


Figure 7.7 (*above*). Photograph of completed rainfall catchment at Mauka I work site (Photo by C. Vandemoer, 1988).

Figure 7.8 (*above*). Photograph of rainfall catchment at Mauka II work site (Photo by C. Vandemoer, 1988).

The harvesting structures worked well during the course of the project, with over 1,000 gallons of water captured in a three month period. Runoff efficiency on the harvesting surface approaches 85 percent, and could be improved by using different materials.

To develop estimates of the quantities of water available from rainfall harvesting surfaces, Tables 7.8a and 7.8b provide estimates of water yield from catchments for different size storms. Table 7.8a provides water yield estimates at a runoff efficiency of 100 percent and Table 7.8b provides estimates for 75% runoff efficiency. Although the quantities may seem small in comparison to Kaho'olawe's overall water needs, rainfall harvesting can be used effectively to meet certain portions of demand, such as base camp requirements, hiking trail requirements and some revegetation requirements. Great quantities of water could be harvested each winter; the only limit (aside from total rainfall) is the size and number of harvesting structures and available storage.

It is not necessary to limit rainfall harvesting structures to those built during the project. Covering the land surface with paraffin, salt, plastic, concrete, asphalt, or other coatings can work equally as well to harvest rainfall. Roof catchments consisting of sheet metal or other substances are also additional possibilities.

Table 7.8 (a). Potentially Harvestable Water at 100 Percent Catchment Efficiency
(in gallons)

Storm Size (in inches)	Catchment Size (in square feet)				
	190	200	400	800	1,000
0.5	5.92	6.28	12.56	25.13	29.9
1.0	118.43	124.6	249.3	498.7	598
1.5	177.7	187.0	374.0	748.0	897
2.0	236.8	249.3	498.7	997.3	1,196
2.5	262.1	296.1	632.2	1,246.7	1,496
3.0	355.3	374.0	748.0	1,496.0	1,870
3.5	415.0	436.3	872.7	1,745.4	2,164
4.0	473.7	498.7	997.3	1,994.7	2,468
4.5	532.9	561.0	1,123.0	2,244.0	2,767
5.0	592.2	623.3	1,246.7	2,493.4	3,141
25	2,969.9	3,701.1	7,402.2	14,804.4	15,558

Table 7.8(b) Potentially Harvestable Water at 75 Percent Catchment Efficiency
(in gallons)

Storm Size (in inches)	Catchment Size (in square feet)				
	190	200	400	800	1,000
0.5	4.42	4.67	9.35	18.7	23.37
1.0	88.8	93.5	187.0	374.0	467.5
1.5	133.2	140.3	280.5	561.0	701.3
2.0	177.7	187.0	374.0	748.0	935.0
2.5	222.1	233.8	467.5	935.0	1,168.0
3.0	266.5	280.5	561.0	1,122.0	1,402.5
3.5	310.9	327.3	654.5	1,309.0	1,636.2
4.0	355.3	374.0	748.0	1,496.0	1,870.0
4.5	399.7	420.8	841.5	1,683.0	2,103.8
5.0	444.1	467.5	935.0	1,870.0	2,337.5
25	2,226.8	2,775.8	5,551.7	11,103.3	11,687.6

Importation of Water

Importation of fresh water to Kaho'olawe was often necessary for island residents at the turn of the century and later. Large barges containing fresh water delivered thousands of gallons of water to Kuhe'eia, Hakioawa and Ahupu bays; the receiving tanks are still in place at Kuhe'eia. At present, the U.S. Navy imports roughly 10,000 gallons of water each month to Kaho'olawe. In addition, water is imported by the 'Ohana when on island, as with other scientific staff when performing work on Kaho'olawe.

Given the size of Kaho'olawe's water demand, the easiest way to meet the demand would be to import water; however, the cost of importation and delivery of water to storage facilities is high. The Navy's system costs approximately $9,000 per month for roughly 10,000 gallons of water to Kaho'olawe. This does not include the costs of getting water to the storage tanks (which involves dragging the water truck onto shore with a large vehicle) nor wages for the delivery, and neglects storage. The costs of civilian transportation of water to Kaho'olawe are higher and in the neighborhood of $10,000 per 10,000 gallons.[3] As with the Navy estimates this does not include the costs of moving water from the boats to the storage tanks. Given the labor intensive nature of importing water, as well as its high cost, large scale importation (particularly for conservation work) is prohibitive.

Desalinization

Desalinization or demineralization of brackish-saline water through reverse osmosis on Kaho'olawe offers substantial opportunities for meeting a certain portion of water demand. With a series of self-contained desalinization units established at critical localities on Kaho'olawe, much of the island's base camp and cultural use area potable water needs could be satisfied through the small scale desalinization of sea water or brackish ground water obtained from dug wells. Small desalinization units have the capacity to reduce total dissolved solids levels in water to the 300-500 part per million (ppm) range. Units are available which produce 2.5-63 gallons per hour.[4]

Reverse osmosis is achieved by applying very high pressure to force sea water through a semi-permeable membrane which removes the total dissolved solids from the "feed" water. The method rejects approximately 98% of the salt from feed water. The small units have wide application in small craft and in rural settings. A power source and routine maintenance are required. Additionally, waste brine must be disposed of.

Other Methods: Direct Interception of Cloud, Mist and Fog Water

When fog or mist is blown through trees, droplets collect on the leaves and drip to the ground. Vegetation takes full advantage of this water source, and even very small amounts of water can mean the difference between life and death in arid lands, such as desert coasts. Fog drip can amount to more than one third of annual rainfall. Often dismissed as "interception", fog drip can be important component of the water budget of an area, and is apparently responsible for the hearty looking condition of some plants on otherwise barren hardpan on Kaho'olawe. In the winter months, fog and mist often enshroud portions of the summit area of Kaho'olawe. Even in summer months, grasses in certain portions of the hardpan are often wet in the early morning hours. 'Ohana members report water soaked sleeping bags after overnight visits to the island's summit, Moa'ula.

The occurrence of fog drip and mist is highly dependent on the moisture, cloud and wind regime of Kaho'olawe. Microvariations in temperature, moisture content, and wind direction may produce substantial variations in the location of fog or mist formation. Clouds brought by the northeast trade winds are swept up the windward slopes of Kaho'olawe, accelerated by the heating of the surface during the day. By night, cooled air drains down the slopes, or is trapped within small depressions on the land surface. The convergence of the warmer air of the constant trades and the cooler air tends, by night, to produce a maximum of cloudiness and mist just below the summit area, at the zone of convergence. During the day, if conditions are favorable, convection and upslope flow and convergence with cooler air at the summit tend to enhance cloud and mist formation in the upper and inland areas of the island.[5]

Interception of fog and mist is accomplished by a number of small scale technologies. A louvered aluminum shade screen, with vertical notches cut into the surface to enhance rapid drainage into the collection device, was successfully applied to capture and quantify the amount of fog drip on Mauna Loa.[6] Other technologies include the use of plastic or metal sheets. Interception of fog drip is also obviously accomplished by the selective planting of species with favorable interception characteristics which include, for example, canopy cover and the form, density and surface texture of the leaves.

Inasmuch as there is little quantification of factors on Kaho'olawe that would allow an estimate of the contribution of fog drip and mist to the overall water demand of vegetation, it is not possible to quantify the needs that fog drip could meet. However, plant species known for their affinity for fog or mist should be selected and used in revegetation efforts.

Summary: Matching Water Demands to Water Sources

This chapter has presented information quantifying both the demand for water on Kaho'olawe as well as the potential sources of water and their possible yield. To match the available supply to a theoretical demand, a number of assumptions were made regarding the future use of the island, with general guidance provided by the Maui County's Kaho'olawe Community Plan. Much of the supply information is derived from research conducted during the project regarding surface and ground water supplies and discussed in Chapters 3 and 4; actual experience with water harvesting facilities and resulting data are obtained from project work conducted in the field between August 1988 and January 1989.

An overview of the demands and their potential supply sources is presented as Table 7.9. Several combinations of supply sources is possible, given the financial, logistical and labor constraints as well as development preferences of the resource management parties. Table 7.9 presents one such supply scenario. In this scenario, the water demand for a fire protection plan was divided into two categories according to use: 1) for the military target area and 2) for base camps. The 50,000 gallon target area supply would be provided by the U.S. Navy. Currently, the Navy plans to use sea water for their fire protection program. However, the environmental consequences of using sea water for fire protection will only serve to worsen erosion conditions in an area of saline sensitive clays. Therefore, the water should be imported or developed by the Navy for this purpose.

The modest estimates here do not purport to support massive large scale development of Kaho'olawe: only the orderly revegetation of the island's environment, the gradual expansion of community access to Kaho'olawe through base camp development, and the continuation of educational and scientific activities focused on increased understanding, knowledge and protection of Kaho'olawe's natural and cultural resources.

It is important to recognize that the only water source "developed" to any extent currently for Kaho'olawe is imported water. There is, as explained throughout this document, considerable potential in the development of precipitation and runoff catchments, and in ground water development. However, high initial costs are associated with achieving the development of all these sources at the level proposed in this document. Costs are discussed as the subject of Chapter 8.

Nevertheless, water development on Kaho'olawe is currently and urgently needed to implement planned revegetation and cultural resource management activities.

Table 7.9. Water Demand and Potential Supply, Kaho'olawe, Hawai'i, 1990

Activity	Annual Water Demand (in gallons)	Potential Water Source & Amount (in gallons)
Soil & Water Conservation		
•2,500 acres on hardpan	350,000	• Runoff 100,000 Rainfall 100,000 Ground Water 150,000*
Kaho'olawe Community Plan		
• Base Camps	90,000	• Rainfall 25,000 Desalinization 65,000
• Cultural Activities	1,000	• Rainfall 1,000 Ground water ?*
• Educational/Scientific Activities	1,500	• Rainfall 1,500
• Fire Protection (Base Camps)	4,000	• Rainfall 1,900 Importation 100 Ground Water 2,000*
Military Use (other than that listed above)	120,000	• Importation 120,000
• Fire Protection (Target Range)	50,000	• Importation 50,000
TOTAL	**616,500**	

See previous chapter for discussion of basis for water demand calculation.
*Ground water is a potential source, and could conceivably supply as much as 100% of all water resource demands on Kaho'olawe. However, it is expected that ground water may not be potable in many places.

Notes to Chapter 7

[1] Many 'Ohana members, for instance, believe all native drought-resistant plants will do well throughout the island regardless of climatic differences. Evidence from the Native Hawaiian Plant Society's planting trials support this position. Native species commonly found in coastal areas like 'akulikuli (*Sesuvium portualcstrum*) and hinahina-kukahakai (*Heliotropium anomalum*) thrive in the area of the northeastern hardpan at an elevation of 1000 feet. Matthew Spriggs (1987) suggests that historically Kaho'olawe's traditional vegetation pattern may have looked similar to that of Waimea-Kawaihae on Hawai'i island as described by archaeologist Holly McEldowney. "There was a coastal strip of fishing settlements and some trees such as coconut. Moving inland were the *pili* or grasslands. *Pili 1* lands are where the grass was an annual community in areas of 10 inches annual rainfall or less; in the Waimea-Kawaihae area this zone was used for taking wild birds and collecting grass for thatching. In basins holding some moisture, the most marginal agriculture--using diversion of ephemeral stream runoff -- was practiced in the late prehistoric/early historic period. *Pili 2* are the perennial grasslands areas of less than 20 - 30 inches annual rainfall with scattered tree and shrubs. *Pili* is used as an agricultural mulch and could have been so used on Kaho'olawe. The next zone inland in the Waimea-Kawaihae area is the lower *Kula* used for agriculture. Most of Kaho'olawe (the western portion) would have been similar to Pili 1 while the wetter parts of the inland plateau would have been Pili2/Kula" (Spriggs, 1987:I-42).

[2] Information regarding military water use from personal communication, Captain G.E. Mittendorff, former Assistant Chief of Staff, U.S. Navy, Kaho'olawe Projects Office, Pearl Harbor, Hawai'i, August 1989.

[3] May actually involve renting the services of military transport or purchase of a large landing craft at regularly-held surplus sales.

[4] HRO, Inc,. Los Angeles, California, personal communication, December, 1988.

[5] J.O. Juvick and Paul Ekern,"A Climatology of Mountain Fog on Mauna Loa, Hawaii Island", 1978 and W.D. Sellers, Physical Climatology , 1972.

[6] Ibid.

CHAPTER 8

The Development and Management of Water and Land Resources

Introduction

The focus of the Kaho'olawe water study was to delineate the sources and occurrence of water on Kaho'olawe, and to match these sources with proposed uses of and existing demands for water. The next phase in the investigation involves the identification of a development plan that provides the mechanism through which to realize land use, water development and water management goals for Kaho'olawe. Within the context of proposed and existing uses, however, it is apparent that the stabilization of the soil, water and vegetation environment on Kaho'olawe is key to the viability of future uses. This imposes an overall guiding factor in the assessment of development strategies, for no development plan for Kaho'olawe could ignore the island's pressing resource management needs.

It is important to recognize that resource development and resource management are two sides of the same coin: responsible, effective and ecologically sound development must also include provision for resource management, protection and stewardship. The development plan is guided by the current goals and proposed land and resource uses of the Kaho'olawe Community Plan, which are described in Chapter 7. The resource management plan is guided by the critical need to control soil erosion, to stabilize archaeological sites, to revegetate, and to manage the development of the ground water and surface water resources of Kaho'olawe.

The proposed development plan described in this chapter consists of both development and management components. The plan is divided into 4 phases, spanning the year 1990 to 2010. The first section of the chapter identifies a detailed strategy for water development and costs for Phase I of the plan. Section two outlines the management strategies needed to protect the water resource. Section three presents the water development/management plan. General resource development and management activities are described, along with an estimated budget needed for implementation.

The estimated costs presented throughout this chapter are based upon 1990 dollars. According to the Economics Department of the Bank of Hawai'i, the Consumer Price Index in 1990 was 138.1. To calculate the value of 1990 dollars to the current year, use the formula - current $ value = 1990 $ x the Current Consumer Price Index divided by the 1990 Consumer Price index (138.1).

Water Development Strategies

There are four major sources of water that could be developed to satisfy the water needs of Kaho'olawe. Each of the four sources - surface water (including precipitation), ground water, importation, and desalinization - could be developed independently to meet demand. The better alternative is to use some combination of development strategies that utilize all possible sources of water. The proposed Kaho'olawe water resource development plan calls for the selective development of ground water resources, large scale rainfall harvesting projects, limited capture of surface runoff, and small scale desalinization. Inasmuch as the Kaho'olawe Community Plan calls for the eventual phasing out of all military use of the island, the water development plan proposed by this document does not recommend additional water development for Navy. Current water uses should remain essentially about the same, with importation as the primary supply for the Navy.

The ultimate cost of development will depend on the selection of the strategy and the relative proportion of water demand met by surface water, ground water, imported or desalinized water. In the following section, a description of the mechanics of development of each source of water is discussed; costs are described in relation to the development of each source independently and then in relation to the proposed combination of sources and uses.

Ground Water Development

One of the most significant findings of the Kaho'olawe Water Study is the discovery of a ground water resource on Kaho'olawe. Even with the discovery, however, there are important uncertainties that remain which complicate immediate development of the resource. The uncertainties - which include aquifer yield and water quality - were discussed in Chapter 5 and are significant enough to mandate additional testing before complete development, especially in view of the large expense involved in transporting and operating a drilling rig on Kaho'olawe.

However, if the aquifer proves to have a significant yield, ground water could be developed to meet all of the soil conservation, fire protection and cultural use needs of Kaho'olawe for many years into the future. Ground water has other advantages, including its ability to be stored and thus its availability at the time of year it is needed, its lack of suspended sediment content and even temperature. We explore here the possibilities of ground water development on Kaho'olawe.

Research and Exploration. The first phase of ground water development on Kaho'olawe would involve the design and implementation of a drilling program to identify aquifer properties such as porosity, transmissivity, hydraulic conductivity, yield, sustained yield, and water quality. Stratigraphic information could be obtained from logging and analysis of wells and drill cuttings. The optimal location of a well field could then be identified from information collected during the research and exploration phase.

Research and exploration would involve the drilling of 6-8 wells at selected localities on the island, and using the wells for both pumping and observation when conducting aquifer tests. Figure 8.1 presents a preliminary identification of test well locations. Further research is required to determine the balance between horizontal (or inclined) wells and vertical wells in the exploratory phase. Water quality samples would be collected continuously during aquifer tests and taken from different depths when the water levels are static. The approximate costs associated with additional ground water exploratory work are identified in Table 8.1.

Development Costs. If ground water is found to be recoverable in sufficient quantities, and is dike impounded water, there are several likely locations for the development of a well field or single well. Ground water development sites are the same as testing sites and are shown in Figure 8.1, indicated by a star surrounded by a dark circle. Site 4A in Figure 8.1 is, from a hydrologic standpoint, a likely location of a promising well. However, it is within the Navy's target area and a well would likely suffer damage from continued explosions in the region. Sites 4B and 4C may hold promise for a well.

Both perched ground water and the basal ground water lens at Hakioawa could also be developed. Perched water might be tapped at the locality identified in Figure 8.1 with a Maui-type horizontal well. Maui type horizontal wells tap dike impounded water through an inclined horizontal well, cutting diagonally across the dikes. Small scale development of the basal ground water lens would involve the cleaning and renovation of existing dug wells and selective felling of kiawe trees to reduce the evapotranspiration demand on the ground water resource. Table 8.1 identifies the expenses involved in dug well renovation.

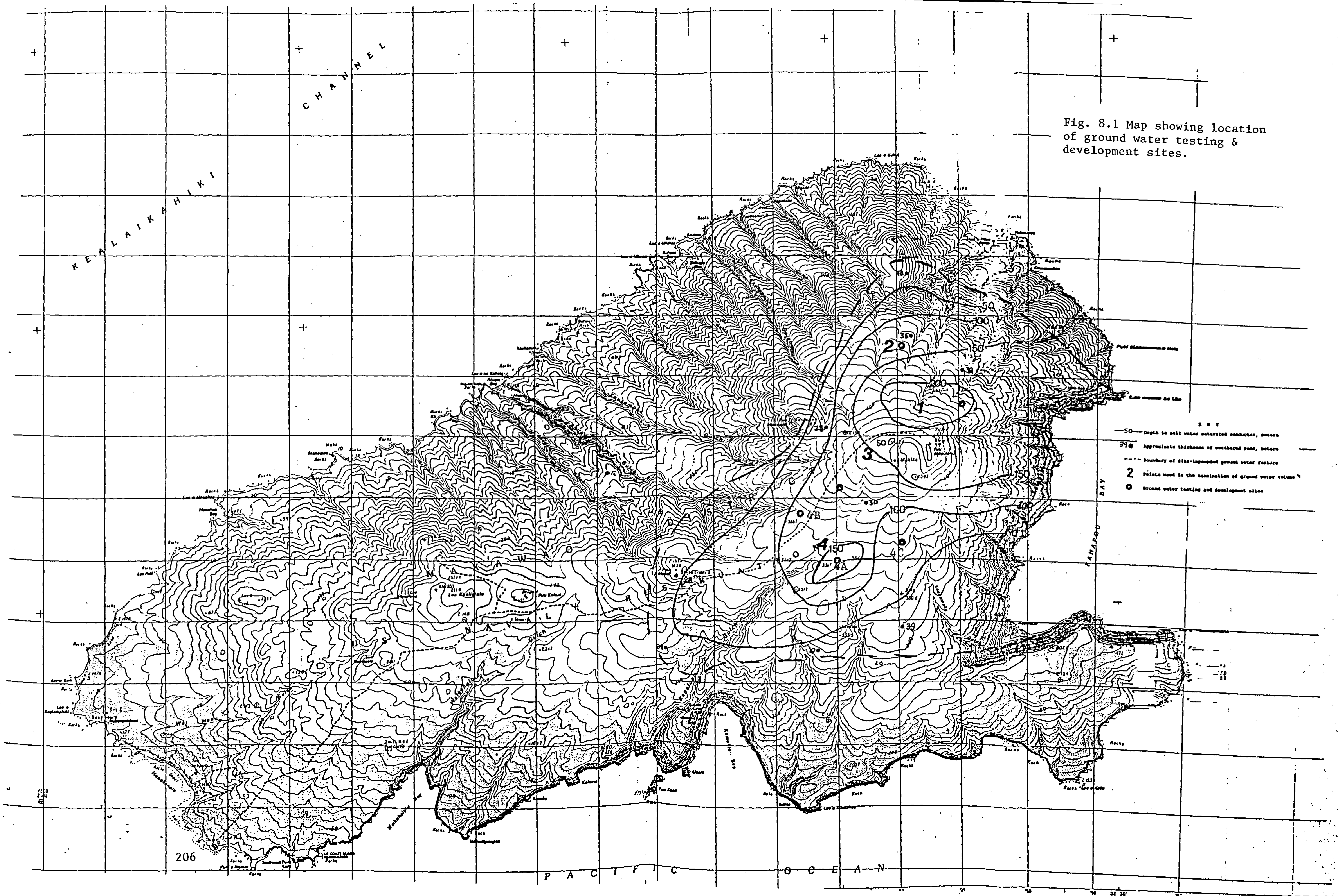


Fig. 8.1 Map showing location of ground water testing & development sites.

Table 8.1. Costs of ground water exploration and well development program, Kaho'olawe, Hawai'i

(based on 1990 U.S. Dollars; does not include costs of environmental assessments)

Budget Item	Description	Estimated Cost[1]
Design of Drilling Program & Analysis of Results; Final Well Completion	• One year • Five professionals	$ 155,000.00
Transport of Drilling Rig to Kaho'olawe	• Barge transport • Transport to on-island locations	$ 26,500.00
Operate Drilling Rig and Drilling of 6-8 holes	• Six holes, 600 feet • $250 per foot • Operation expenses (120 days @ $2,600 per day)	$1,212,000.00
Water Quality Testing	• 1 staff person for collection • 24 days • 32 samples analyzed@ $200 each • treatment by mixture or desalinization	$ 45,000.00[2]
Water Well Development	• 3 wells @ $16,000 each	$ 48,000.00[3]
Renovation of Existing Dug Wells Clearing	• Supplies/Equipment • Transportation • Labor/Site clearing	$ 53,000.00
Additional related Expenses	• Storage for 350,000 gallons • Distribution Systems/Pumps	$ 389,000[4]
	Total Estimated Cost:	**$ 1,928,500.00**

[1] Many in-kind contributions would lessen the cost of the program, including use of Navy and state transportation, equipment and personnel, and water quality testing laboratories.

[2] Assuming 3-8 day aquifer tests.

[3] Includes gravel, grout, casing and related well development costs.

[4] See text for assumptions regarding storage/distribution facilities used in this estimate.

The wells drilled during the exploratory phase in the dike impounded region must be capable of conversion to water wells in order to avoid any additional large expense for drilling. If the wells are designed as such, then the conversion could be done shortly after the testing while equipment and personnel are still available, at an additional cost dependent upon the number of wells converted. In Table 8.1, a cost of $16,000 per well is identified for the development of possibly three wells.

Additional Related Expenses. With ground water development, there will be a need for distribution and storage facilities, including pumps, pipelines, sprinklers, drip irrigation systems, and pressure control facilities. Pumps on Kaho'olawe could be driven by wind or solar energy to avoid fuel generation costs. Adequate storage should always be available.

Ground water is projected to satisfy the 350,000 gallon annual water demand for revegetation efforts, while military demands will be fulfilled by imported water and the Kaho'olawe Community Plan demands fulfilled by a combination of surface runoff, desalinization, and rainfall catchments. To satisfy the annual demand for revegetation efforts, four 25,000 gallon tanks, distributed over the hardpan area, could store sufficient water which would be pumped at intervals throughout the year. At $9,000 per tank, this adds $36,000 to the total. If a drip irrigation system is developed for a 2,500 acre area, and assuming adequate pressure can be supplied through gravity, an additional $75,000-$100,000 could be required annually to complete the system for revegetation goals discussed in Chapter 7. In addition, installation costs for personnel, supplies, equipment and transportation are necessary. Table 8.1 identifies this cost as part of the entire ground water effort proposed for Kaho'olawe.

Surface Water Development

The development of surface water, as proposed in this plan, includes both precipitation and surface runoff development through water harvesting techniques. As specified in Table 7.9, Chapter 7, the development of surface runoff and precipitation facilities are expected to harvest a minimum 229,400 gallons of water per year, given the full structural development of this capacity. If necessary surface water could be used to supply much more of demand. For the purposes of this discussion, we assume rapid development of the facilities over the next 4 years to capture and store rain water on Kaho'olawe. This translates into the installation of a certain number of structures per year.

Again, the guide for the location of these facilities, and thus the development of an orderly plan, is the Kaho'olawe Community Plan in the context of revegetation, educational and base camp needs. Figure 8.2 locates proposed rainfall and runoff catchment facilities. We first discuss rainfall harvesting and then surface water runoff.

Rainfall Harvesting Costs. The development of rainfall harvesting systems on Kaho'olawe is the most viable and economical way of capturing clean, potable water. The capture and storage of water at each of the proposed 4 new base camps and expansion of the current demonstration catchment at Hakioawa can be accomplished through the construction of five 200 square foot catchment surfaces with appropriate storage and distribution facilities. Each base camp could capture in an average year's time (25 inches of rainfall) approximately 3,000 gallons of water. Expansion of the catchment surface to 400 square feet could capture roughly 5,000 gallons of water for each camp. An 800 square foot catchment surface could capture over 10,000 gallons of water per base camp. Storage facilities and distribution systems will be required.

Because of the uncertainty of ground water yield and the time necessary for its development, annual capture of 250,000 gallons of rainfall is desirable for the hardpan area to fulfill the demand for critical revegetation/conservation work, educational, scientific and cultural purposes. The construction of larger catchment surfaces is necessary. Catchment structures are proposed with a total surface area of 18,000 square feet. According to data presented in Table 7.8(b), approximately 250,000 gallons of water could be captured annually. In the case where ground water development is not pursued, conservation water demand could be fully supplied by rainfall harvesting. A total catchment surface of 25-30,000 square feet could easily yield the 350,000 gallons total needed annually for conservation work on the hardpan.

The costs of constructing a 200 square foot rainfall catchment is presented in Table 8.2 and is based upon the construction of demonstration projects during the Kaho'olawe Water Study. Costs include lumber, hardware, nails, catchment surface material, plumbing, miscellaneous supplies, storage tanks, transportation, labor costs. Construction of larger catchment structures will no doubt lead to greater savings per square foot of catchment surface.

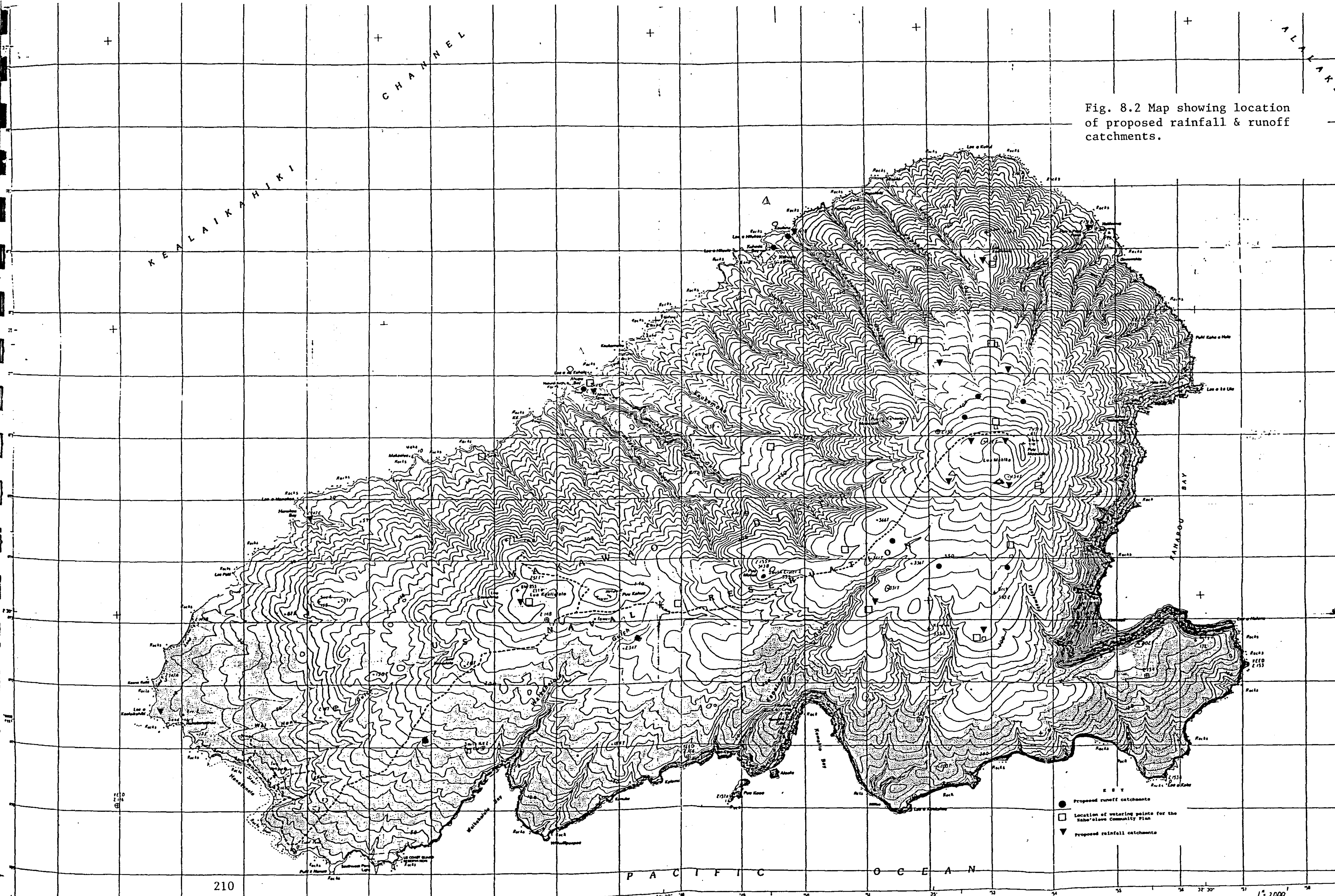


Fig. 8.2 Map showing location of proposed rainfall & runoff catchments.

Table 8.2. Costs of rainfall catchment construction, Kaho'olawe, Hawai'i, for 200 square foot surface, with storage.[1]

Description	Cost (in 1990 dollars)
1. Construction Materials	
Lumber	$ 400.00
Hardware	100.00
Surface	100.00
Plumbing	325.00
Storage[2]	950.00
Miscellaneous	250.00
2. Transportation	
Private Helicopter	800.00
3. Labor	
2 @ 4 days @ $120/day	960.00
Cost per catchment, including storage:	**$ 3,885.00**

[1] Cost estimates based upon Kaho'olawe Water Study project activities, 1988-1989. Bulk purchases would reduce costs per square foot of catchment surface for large catchment structures.

[2] The storage tank would be a corrugated metal water tank with a vinyl liner, with a storage capacity of 2,000 gallons at approximate cost of $950. Again, larger storage tanks would result in significant lower costs per gallon.

Surface Runoff Harvesting Costs. The capture of surface water through the diversion and storage of runoff was discussed in Sections 2 and 3, and was used extensively on Kaho'olawe in the past. This development component contemplates the renovation of existing runoff catchment facilities at Ahupu and Kuhe'eia, providing a runoff storage capacity in excess of 600,000 gallons, and the development of small runoff facilities on the hardpan with a total capacity of 100,000 gallons.

The renovation of existing facilities includes engineering adjustments to diversion facilities and grades, excavation, repair and lining of masonry tanks, installation of filtration and disinfection devices, and rehabilitation of distribution facilities. Estimated costs of renovation of the two existing facilities ranges from $40,000-$60,000, depending on the availability of labor, materials, transportation and equipment.

It is important to note that coastal runoff catchments would follow in the later phase of Kaho'olawe's water development plan, when revegetation and soil stabilization is well underway and has slowed erosion. Sediment-laden runoff from unvegetated slopes would only serve to fill the catchments with silt.

The capture of surface water on the hardpan area for revegetation purposes can be accomplished through the construction of facilities that channel water into existing bomb craters and natural depressions on the land surface or by covering the land surface with a synthetic cover, such as asphalt, salt or plastic, and diverting water into a storage facility. For the runoff diversion, filtration will be necessary for further use of water; in addition, the high sediment load of surface runoff may in fact act to fill the depression or bomb crater. A synthetic surface will not require such filtration and there will be minimal sedimentation of storage facilities. Surface runoff harvesting is proposed for the hardpan areas located in Figure 8.2, and consists of the construction of five runoff catchment facilities, each with capacities of 12,000 gallons, for the capture and diversion of runoff into several natural and bomb-produced depressions on the hardpan area. The relative costs of alternative surface runoff harvesting structures are presented in Table 8.3.

Table 8.3. Costs of Runoff Harvesting Systems, Kaho'olawe

Harvesting System	Description	Costs per Catchment (in 1990 dollars)
1. Renovation of Existing Cisterns	Labor & Materials	20,000.00
	Transportation	20,000.00
2. Diversion into Natural Depression or Bomb Crater[1]	Labor (2 people)[2]	1,200.00
	Materials/Equipment	350.00
	Filter	250.00
	Distribution	300.00
	O & M	100.00
	Transportation	900.00
	[Total Cost per Structure	2,650.00]
3. Lining of Surface with Synthetic Material for 5,000 square feet	Plastic	2,500.00
	Asphalt[3]	40,000.00
	Concrete	5,000.00
	Paraffin	20,000.00
	Salt & mechanical alteration	3,750.00

[1] Data based on construction of .2 acre runoff catchment with storage capacity of 13,321 gallons on Kaho'olawe, January, 1989.

[2] Based on 2 people, 4 days, 10 hours per day @ $15.00/hour.

[3] Does not include an estimated $20,000 in equipment needs or environmental assessment cost.

Desalinization

Desalinization of approximately 65,000 gallons of water on an annual basis for the three base camps on Kaho'olawe by small desalinization units is proposed as a major water development step. Desalinization of both sea water and brackish ground water is contemplated. The costs of proposed desalinization, presented in Table 8.4, include the unit itself, purchase of a power source, storage and distribution facilities, operation and maintenance of the unit, and other miscellaneous expenses associated with maintaining the efficiency of the reverse osmosis membrane.

Table 8.4. Costs of Desalinating Ocean and Brackish Water, Kaho'olawe, Hawai'i

Unit	Description	Cost (in 1990 dollars)
1. Desalinizing Unit, with filtration & disinfection units[1]	1,500 gallons/day	10,000.00
2. 1.6 HP Power Source, Fuel, Operation & Maintenance	Generator	4,500.00
3. Storage Tank[2]	10,000 gallons	9,000.00
4. Distribution Facilities	To and From unit	1,000.00
5. Operation and Maintenance	Annual	10,000.00
6. Labor	Installation	750.00[3]
	Total Cost Per Base Camp $	**35,250.00**
	Total for 3 Base Camps:	**$105,750.00**

[1] HRO Systems Desalinization Unit, HRO, Inc., Los Angeles, California

[2] Storage facilities for rainfall and desalination units should be combined where possible, reducing overall costs.

[3] Labor costs will vary according to time it takes for installation.

[4] Does not include cost of environmental assessments.

Importation of Water

As mentioned earlier, importation of water, albeit costly, has been practiced for several decades. The research conducted as a part of this project recommends the continued importation of water to meet certain needs, but stresses the development of indigenous sources of water where possible. If all the water resource needs of Kaho'olawe were met with imported water, the annual cost could range between $600,000 and $800,000, including delivery to island and transport of water to needed localities. Over a four-year period, this represents an investment of $2.4 - $3.2 million dollars. For the purposes of developing cost estimates for this report, imported water is directed toward the continued supply of military needs. Table 8.5 presents preliminary cost estimates of some alternatives.

Table 8.5. Costs of Importing Water to Kaho'olawe

Demand	Unit Cost (in 1990 dollars)	Annual Cost (in 1990 dollars)
1. Meet 120,000 gallon Navy demand[1]	$9,000/10,000 gallons[2]	108,000.00
2. Meet 616,500 gallons island demand		
120,000 Navy	$9,000/10,000 gallons	108,000.00
496,500 Other[3]	$10,000/10,000 gallons[4]	496,500.00

[1] Does not include the 50,000 gallons for fire protection in the target range.

[2] The cost of importation for the Navy water supply is an estimate and does not reflect actual cost.

[3] This includes 54,000 gallons of water for fire protection program in camps and the target range.

[4] The cost of private barge transportation is higher than Navy costs. This does not include costs of transporting water to desired localities nor storage and distribution costs.

Summary of Development Options and Costs

Given the broad outline of costs of water resource development discussed, Table 8.6 brings this information together and presents the proposed development scenario as an estimated budget for Phase I of water development work. It is important to remember that many of the costs described are <u>start-up</u> costs, which are always more expensive; once the systems are in place, average annual costs will drop significantly. With the exception of desalinization, operation and maintenance costs for construction, transportation and accommodations for project personnel while on-island have not been fully identified in these estimates.

Table 8.6. Summary of Costs for Proposed Water Resource Development Plan for Kaho'olawe

The values reflect one time development costs, 1990 dollars.

Water Source	Percent of Demand Supplied[1] KCP[2]	Military	Revegetation	Development Costs
Imported Water	0	100%	0	$ 108,000.00[2]
Surface Runoff				
Renovation of existing facilities	3%	0	10%	60,000.00[3]
Surface Water Catchments	0	0	15%	55,000.00[4]
Ground Water Resources	0	0	43-100%	1,612,500.00[5]
Desalinization	67%	0	0	105,750.00
Rainfall Catchments	30%	0	30-75%	555,000.00
TOTALS	**100%**	**100%**	**100%**	**2,523,250.00**

[1] This is one possible scenario of a means to meet water demands. Any combination of alternatives could be developed from these data.

[2] This figure reflects annual costs of this water source.

[3] This figure reflects the median of the cost range $40-60,000 identified for the renovation of catchment facilities.

[4] This amount is a minimum figure. For a synthetic lined diversion catchment cost for the liner would need to be added and would need to be determined later when dimensions and characteristics are chosen.

[5] Amount could be significantly reduced with in-kind contributions of transportation, personnel, equipment and accommodations by U.S. Navy and State.

[6] Does not include cost of environmental assessments.

The cost estimates identified in Table 8.6 will be used in Section 3 of this chapter in phased water development plan. However, before the plan provisions are formulated, management activities must also be identified. As discussed earlier, water development must occur in conjunction with water management for effective, ecologically sound natural resource development. Because of the deteriorated state of Kaho'olawe's natural environment, resource management is a necessary prerequisite for further development. In the next section, a plan for the management of Kaho'olawe's surface, ground water, land and vegetation resources is proposed.

Development of Planned Approaches

The development of approaches to the rehabilitation and management of Kaho'olawe's natural resources must be based upon a sound understanding of the physical principles controlling the movement of soil and water on the land surface. Once the physical framework is grasped, resource management strategies follow with relative ease. However, effective resource management must be guided by a set of institutional arrangements and implementation tools designed to get the job done. In addition, the lack of a coordinated approach to resource management on Kaho'olawe contributes to the deterioration of the island's environment and cultural resources. A re-examination of the conflicting objectives for the use and management of Kaho'olawe's resources would assist overall efforts to rehabilitate the island [1]

In this context, it imperative that a planned and coordinated approach be developed so that swift and effective corrective action can be taken on Kaho'olawe's behalf. The approach must be based on the correct physical interpretation of the processes producing environmental degradation and the effective application of corrective remedies.

The framework adopted throughout this report is that of a watershed, where soil and water processes are delineated in comprehensive fashion within the watershed unit. A watershed is a logical unit for resource development; it also is the only unit that can be used to effectively design and implement protective resource strategies on Kaho'olawe.

All erosive processes must be looked at within the comprehensive framework of a watershed; to do otherwise risks the oversight of very important processes. For example, the planting of tamarisk trees on the hardpan area was designed to control wind erosion and to begin to develop and environment where plants could have shelter and flourish. The trees were planted perpendicular to the strong and consistent tradewinds to address wind erosion, but were planted parallel to the direction of water flow. As a result, the tamarisk trees tend to channel runoff and may have accelerated gullying in the present hardpan area (Figure 8.3). These areas are now in critical need of erosion control strategies designed to counteract the effects of the planting direction on water-induced soil erosion. This is an example showing how the long-standing debate of wind versus water erosion prevents comprehensive planning on Kaho'olawe.

Figure 8.3. Photograph of gullies developing beneath tamarisk trees on Kaho'olawe. The trees drop salt on the ground which then causes the soil surface to seal. As water moves downslope along the tamarisk treelines, velocities increase. Eventually, a headcut develops (Photograph by the Protect Kaho'olawe 'Ohana, August 1988).

Selection of Watersheds

The basis of the planned approach to resource management on Kaho'olawe is watershed management, and begins with the ranking of watersheds according to their relative priority for restoration and management. A set of criteria describing the physical condition of Kaho'olawe's environment are used to analyze and rank priority watersheds. The criteria include:

Length of Overland Flow
As described in the surface water section, the longer the uninterrupted slope length, the more erosive water becomes; breaking up the length of overland flow with terraces and other structures slows water down and permits infiltration. The selection of watersheds was based on overland flow lengths of .45 mile or greater.

Drainage Area
The implementation of resource management practices in large drainage areas

affect a greater quantity of water. For this study, watershed areas of .8 square miles or greater were chosen.

Region of hardpan area
Some regions of the hardpan area have more vegetative cover than others; there are also areas on the hardpan that are becoming more dissected than others. This study has identified regions 1 and 4 in Figure 8.4 as the most critical erosive areas.

Slope
This is another factor relating to the erosive energy of water, with steeper slopes creating more erosive energy. A slope of 7.5 % or greater was the criterion for this study.

Number of Tributaries
The more tributaries, the more likely the presence of additional gullies and increasing dissection of the watershed. For this study, one or more tributaries was the criterion.

Density of Archaeological Sites
This factor adds priority to any watershed because of the existing legal mandates for archaeological site preservation. The greatest concentration of archaeological sites is on the hardpan area, Region 1 identified in Figure 8.4.

Gully Development and Soil Erodibility
This factor describes the condition of rill and gully development in a watershed and the relative erodibility of soils. The criteria are intended to indicate certain critical areas.

Given the criteria above, a search condition was constructed for the watershed data base. Table 8.7 identifies the selected watersheds that met the criteria. Figure 8.4 shows the location of these priority watersheds.

Table 8.7. Priority watersheds for Rehabilitation on Kaho'olawe[1]

Hakioawa Watershed	Pali o Kalapakea 4
Papakaiki Gulch	Hulakao Gulch
Papakanui Gulch	Kaukamoku Gulch
Kaulana Gulch	Kaneloa Gulch
Ahupu Gulch	Kaukamaka Gulch

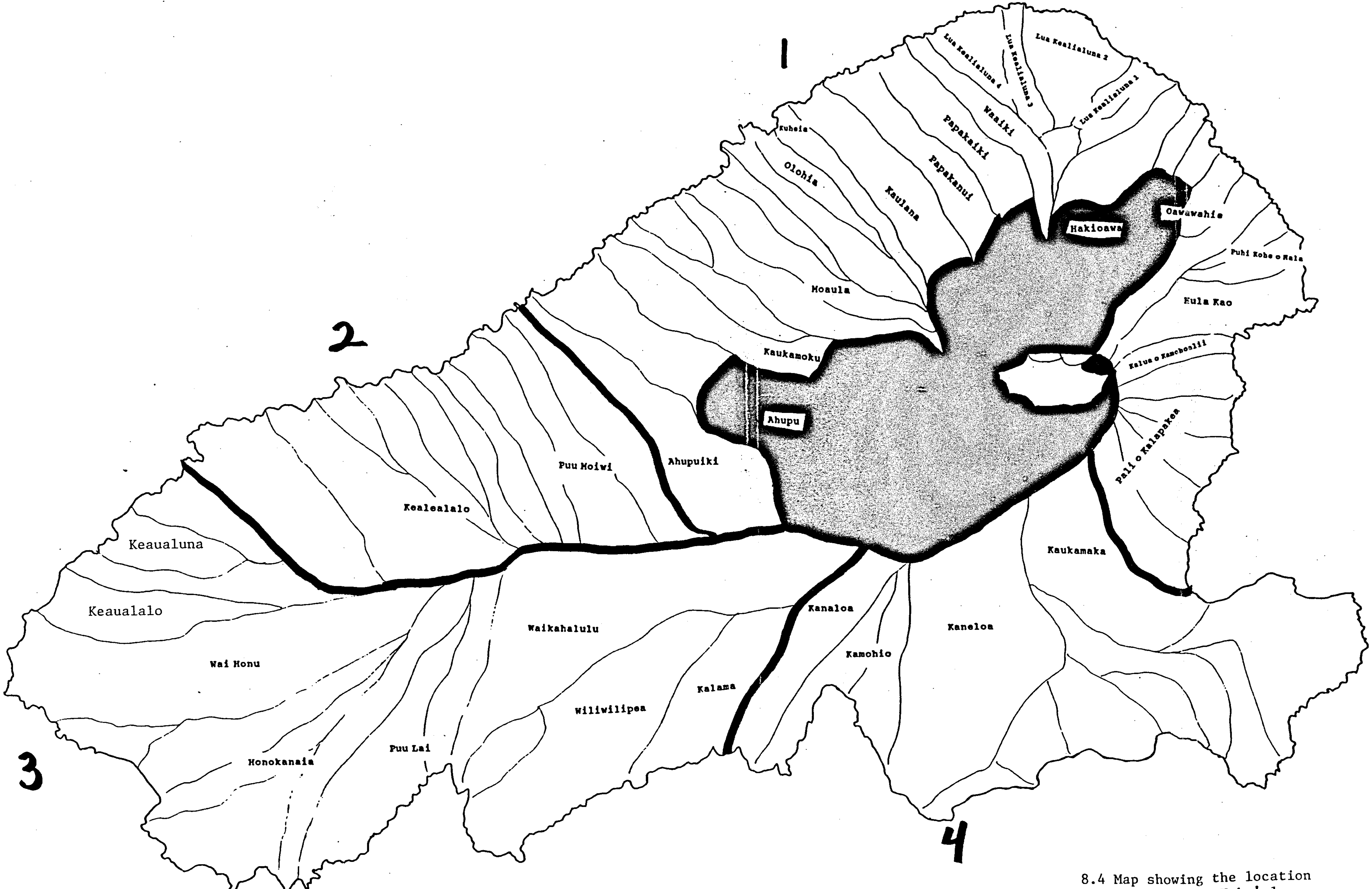
[1] Based on Natural Resource Management Criteria developed by the Kaho'olawe Water Study, 1989.

This list forms the basis of initial resource management work identified in the next few pages.

Identification of Problem Areas and Potential Solutions

Identification of major problem areas involves both an isolation of critical areas as well as a specification of the kind of water resource problem experienced. For example, the length of overland flow may be a problem in one watershed, while mass wasting of gully side slopes may be a serious problem in another watershed. Although these problems are interrelated, one aspect of the cycle of soil erosion may be more dominant in one watershed than in another. Moreover, the density and scale of these problems will vary within watersheds. The identification of problems obviously assists the development of control strategies and is important in determining the type of structures, materials and logistical support required. Table 8.8 identifies several common problems in Kaho'olawe watersheds and possible solutions.

Table 8.9 presents an estimate of the number and type of structures required to rehabilitate and manage the soil, water and vegetation environment on Kaho'olawe in each watershed selected in this study.



8.4 Map showing the location of watersheds on Kaho'olawe in critical need of soil conservation practices.
Demarcates Quadrants 1 - 4
Shows the hardpan in Quadrants 1&4

Table 8.8. Major Problem Areas, Kaho'olawe Watersheds.

Problem Area	Possible Solutions
Soil Erosion	
Headcut advancement	• Headcut control measures
Gully deepening	• Check dams • Headwater control
Gully widening	• Check dams • Bank protection • Headwater control
Mass Wasting	• Erosion netting • Revegetation • Headwater controls[1]
General soil loss through sheet flow	• Sediment detention basins • Terracing • Check dam structures • Revegetation of barren slopes
High water velocities on slopes	• Terracing • Development of vegetation-lined waterways • Detention basins • Check dams • Erosion netting
Channeling of Water through tree lines	• Check dams • Headcut control measures • Erosion netting
Archaeological site destruction by flowing water	• Terracing on upslope side • Erosion netting • Terracing on downslope side • Diversion of water around site
Roads and Runoff generation	• Selective placement and engineering of roadways • Zoning critical areas which prevent road cutting

[1] Headwater controls refer to a variety of strategies by which to control runoff in the contributing area above the erosion site. Vegetation, erosion netting, small scale terracing, and other measures are included.

Table 8.9. Estimate of Soil & Water Conservation Structures Needed for Critical Watersheds. Kaho'olawe, Hawai'i, 1989

Watershed	Check Dams[1]	Planting[2] (acres)	Headcuts	Terraces[3]	Netting[4] (acres)
Hakioawa	50	400	75	25	10
Wa'aiki	10	100	20	5	5
Papakanui	27	150	20	8	8
Kaukamoku	10	125	10	10	9
Kaulana	8	200	10	5	10
Ahupu	30	500	25	15	50
Kaneloa	25	100	20	8	15
TOTALS	**185**	**1,675**	**195**	**86**	**119**

[1] Number of dams calculated according to the methods outlined by Heede (1967). The size and type of check dam varies with location.

[2] These values represent the areas most critically in need of revegetation efforts in the critical watersheds outlined in the text.

[3] Planted according to the pattern outlined in the text.

[4] Erosion netting strategically placed in channel bottoms or on gully side walls. Value represents the number of acres covered.

Managing Water Resource Development

The development of water on Kaho'olawe has its attendant management requirements. The fragile and deteriorated nature of the soil and vegetation environment, and the probable limited quantity of ground water, suggest strict attention to the management of the resource environment. As has been described throughout this document, there are current critical resource needs that demand attention, in addition to new management requirements imposed by either surface or ground water development.

For ground water resources, the limited character of the resource will mandate strict pumping, development and use requirements. Moreover, ground water recharge areas will need to be identified and strategies developed for recharge. The development of ground water on Kaho'olawe, because of the island's unique historical, current and cultural significance to the people of Hawai'i, must also be seen as requiring a public decision-making process regarding the exploration, development and allocation of water use.[2]

The development and control of surface water resources will require stricter land use controls than exist at present, especially for roads and off-road vehicle use. In addition, revegetation is key to the control of surface water resources, and revegetation efforts must continue on Kaho'olawe.[3]

Finally, soil and water conservation efforts, as development strategies, must achieve greater coordination and develop common understandings of resource problems and their solutions on Kaho'olawe. Mutually beneficial and effective strategies for the management of land and water on Kaho'olawe, which combine rather than cause competition among agency resources, can and must be developed.

WATER DEVELOPMENT/MANAGEMENT PLAN

The proposed development plan for Kaho'olawe is based primarily on the recommendations of the County of Maui's Kaho'olawe Community Plan, developed in 1981. The Plan is guided by four major planning standards and principles which define a phased development program covering a 15 year period The principles were developed to guide the multiple use of the island's resources in the context of cultural use, land use, and military use of Kaho'olawe. The major guiding principles include:

1. Preservation, restoration, and enhancement of archaeological sites;
2. Erosion control, restoration and replenishment of Kaho'olawe's vegetation resource;
3. Eradication of goats;
4. Gradual reduction and eventual elimination of military activity of Kaho'olawe;
5. Ultimate return of the island to Maui County and development of Kaho'olawe into a cultural park.

Several specific activities and project locations were identified to meet each of the principles.

The Kaho'olawe Water Study directed its efforts toward the identification of the water resources and natural resource management requirements needed to support the activities specified by the Kaho'olawe Community Plan. Indeed, one major conclusion of the study is that water development, management and control is vital to the achievement of any land use development plan for the island. Without an effective water control strategy, little hope can be held for the preservation of the cultural, soil and vegetative resources of the island. The immediate control of the water, soil and vegetative environment is thus considered the first and primary priority of the study's recommended plan.

Proposed Phased Water Development Plan

Four phases of water resource development are recommended, covering a period of 20 years. Given the principles listed above as guiding factors, the following plan lists the elements of proposed water development on Kaho'olawe that supports the objectives of the Kaho'olawe Community Plan.

Phase 1: 1990 - 1995

In the first five year period, an accelerated program of water resource development activities is implemented. Significantly, it is assumed that within the first 2 years, there exists a long-term funding source and strategy for activities, and that Kaho'olawe's revegetation is a priority for federal, state, local and community agencies.

Groundwater

a. Develop and execute drilling program for the determination of the aquifer and water quality characteristics of Kaho'olawe's ground water resource. Identify total amount of water stored in aquifer and its sustainable yield (determined by aquifer characteristics and the quantity of recharge to the aquifer).

b. Drill and develop 2-3 wells at strategic localities in the dike-impounded aquifer for use in revegetation and fire protection efforts.

c. Construct distribution facilities and storage for 350,000 gallons.

d. Investigate the use of existing craters and other depressions for both short term storage and recharge.

e. Renovate existing wells, clear *kiawe* trees, and treat ground water quality in basal lens as needed using reverse osmosis technologies.

Rainfall Harvesting

a. Increase storage capacity at existing rainfall catchments and improve existing harvesting surfaces.

b. Build additional rainfall catchment structures and increase capacity to 250,000 gallons for use in supplying cultural, religious, and scientific activities on the island's summit area.

c. Construct distribution facilities to support revegetation activities. A stepped program to revegetate on a system of terraces and check dams, plus selective planting on the contour in critical areas could be expected to treat 10,000 acres during his first five-year period.

d. Build distribution and storage facilities for two permanent base camps in summit area.

e. Develop catchments for base camps at Hakioawa, Ahupu, and Kuhe'eia; develop storage capacity for 10,000 gallons at each locality for domestic and small planting/revegetation efforts.

Desalinization

a. Installation of three desalinization units at the primary coastal base camps of Hakioawa, Ahupu, and Kuhe'eia.

Runoff Control

The primary problem in the first few years of surface water development is the high sediment concentration of runoff. Therefore, this plan proposes to stabilize the soil and water environment through check dams, terracing and revegetation first before any major surface water development is contemplated. Depending on the commitment of time and resources, this task could be accomplished for key watersheds within a 5-10 year period, or it could take up to 40 years.

a. Construct several check dams in key eroding areas of Kaho'olawe's summit to slow the velocity of water and capture soil moisture for revegetation efforts.

b. Construct and terrace critical headwater areas so as to slow the velocity of surface runoff and to capture surface moisture.

c. Construct sediment detention basins for existing runoff catchments on island.

d. In combination with the above efforts, revegetate and stabilize 10,000 acres of Kaho'olawe's summit area.

Phase II: 1995-2000

In the second five-year period, the program for water resource development activities is well established and continues with support from the federal, state, local and community agencies.

Ground Water

a. Continuation and completion of drilling and well development program, with the construction of one additional well in the central portion of Kaho'olawe. [Note: reduction in Navy use of the island is contemplated in the Kaho'olawe

Community Plan, and continued clearance of ordnance, will essentially "free-up" the central portion of Kaho'olawe for development and soil and water conservation activities.]

b. Increase storage capacity for ground water by 650,000 gallons, bringing total stored ground water on Kaho'olawe to 1,000,000 gallons (3.6 acres-feet).

c. Construct distribution facilities to convey ground water to project sites on Kaho'olawe, as contemplated by the Kaho'olawe Community Plan. In particular, irrigation facilities to enhance the revegetation effort and fire protection dominate construction activities.

d. Installation of monitoring devices for ground water management purposes. Both dike-impounded and basal ground waters are monitored, as is the water quality of each source.

e. Design and initiate a research and testing program for ground water recharge strategies. Research is directed toward analysis of the impact of soil and water conservation activities on spring development and the use of existing craters for ground water recharge. Testing identifies a small demonstration project.

Rainfall Harvesting

a. Continue and accelerate an aggressive program for rainfall harvesting and storage. Total rainfall storage capacity on Kaho'olawe increased to 350,000 gallons annually. Harvested rainfall is used for revegetation, Kaho'olawe Community Plan activities such as base camp development, trials and scientific research. If ground water quality is poor, harvested rainfall could serve as a source for mixing and water quality improvement.

b. Construct distribution facilities to assist in revegetation efforts. The goal over this second five-year period is to increase irrigated acreage supplied by harvested rainfall.

c. Design and plan increased distribution of storage facilities to selected areas of Kaho'olawe. For example, a summit, gravity-fed distribution system could distribute water to small tanks (8,000 gallons or less) in lower sections of island presumably to be used for revegetation, drinking water supplies, Kaho'olawe Community Plan activities, and scientific purposes.

Desalinization

a. Installation of three desalinization units at the coastal base camps as identified in the Kaho'olawe Community Plan.

b. Continued maintenance on existing units.

Runoff Control

a. Continuation of soil and water conservation and revegetation activities to control sediment concentrations and runoff velocities.

b. Construction of 3 artificial runoff harvesting structures using plastic (or other materials) as a runoff surface, with storage facilities for 20,000 gallons and accompanying distribution.

c. Continuation of construction of sediment detention facilities for existing surface water catchments. Operations, maintenance and data collection for existing facilities.

The completion of the first ten years of project operation with adequate financial, technical and logistical support, will have produced a combined water resource storage capacity of 1.52 million gallons, with 450,000 gallons replenishable through rainfall on an average basis. More than 10,000 acres could be selectively irrigated with this amount of water given the development capability for revegetation accomplished during the first two phases of work, stabilizing current critically-eroding portions of Kaho'olawe watersheds.

If ground water is found to be usable from both a supply and quality standpoint, and if recharge strategies are proved to be effective, this combined capacity plus additional ground water development may be sufficient to supply Kaho'olawe Community Plan activities contemplated to date. An accelerated revegetation program could be accommodated through ground water development, subject to the limiting conditions of the aquifer and its recharge.

Phase III: 2000-2005

Since the first two phases of work accomplished significant water resource development, the major activities accomplished during the third phase focus primarily on distribution of water to support revegetation needs in critical areas. Additional capacity development may be derived either from ground water, rainfall harvesting, or runoff catchments. Land use will increasingly shift toward Kaho'olawe Community Plan activities, with continued phase-out of military use as contemplated in the community plan. The overall focus is an accelerated program of revegetation, archaeological site stabilization, and increasing community access through the development of the Kaho'olawe Community Plan Cultural Park.

Ground Water

a. Continued pumping and storage as dictated by the physical conditions of the aquifer, annual recharge and water quality. Overall capacity should be increased by 200,000 gallons to 1.2 million gallons.

b. Construction of additional distribution facilities as needed in the selective irrigation of 7,000 acres.

c. Implementation of ground water recharge program, if found to be feasible during Phase I and II of the proposed water development program.

Rainfall Harvesting

a. Increase of storage and harvesting capacity (if needed) to supply revegetation efforts. Base camp and other Kaho'olawe Community Plan needs could also be supplied by rainfall. Overall capacity could be increased by 50,000 gallons (or more) as needed.

b. Accelerated construction of distribution facilities for revegetation and Kaho'olawe Community Plan activities.

Desalinization

a. Installation of three desalinization units at the coastal base camps as identified in the Kaho'olawe Community Plan.

b. Continued maintenance on existing units.

Runoff Catchment Development

The efforts of revegetation and soil conservation strategies during the previous phases will result in stabilization of the hydrologic environment such that small scale runoff catchment development may be possible.

a. Design and develop small-scale, off-stream runoff catchments and associated erosion control and sediment detention structures at key locations within selected watersheds. Total design capacity could consider as much as 100,000 gallons, in singular or combined storage.

b. Construct distribution facilities for use of harvested surface water.

Phase IV: 2005-2010

The accelerated program of water development contemplated in the first three phases of this plan is designed to develop and provide the capacity for a variety of uses as well as resource stabilization through effective soil and water conservation. If followed, in the year 2005, a significant storage capacity for water, in combination with infrastructure development for revegetation and Kaho'olawe Community Plan activities, would provide flexibility and resources to continue the restoration and use of Kaho'olawe Community Plan by the State of Hawai'i and its citizens.

Consequently, water development activities and costs will diminish to those of monitoring, operation and maintenance of water facilities and associate projects. Other costs, such as for soil and water conservation and revegetation may continue to grow, until enough of the island is stabilized to provide for other activities. Eventually, these costs and activities will diminish as the environment is stabilized. Significantly, the long activities are postponed in the present, the more significant island deterioration -- and the cost of reclamation -- becomes.

No further additional water resource development is contemplated during this phase, with the exception of continued rainfall harvesting development on an as-needed basis. Instead, the stabilization and revegetation work can and should continue and is strongly recommended.

The vision of Kaho'olawe as, once again, "the little green island" can be fulfilled only through the proper and careful development of water and stewardship of the land base through soil and water conservation. This 20 year plan provides a stepping stone to that future.

Table 8.10 presents the 20 year , phased budget for the implementation of the Kaho'olawe water development and resource management plan. Overall costs were based on research, actual costs developed from the demonstration projects, and project costs. Operation and maintenance costs were added to the development costs to sustain the various program components. A construction allowance cost of 47% was added to overall project costs and include 15% for construction 12% for transportation, 10% for engineering and 10% general labor and administrative support.

The total cost for program implementation is approximately $15 million over a 20 year period. Funding for the program should not rest solely upon the State of Hawai'i and federal and private sources should be pursued. Chapter 9 identifies a series of recommendations to assist in the implementation of the Kaho'olawe water resource development/management plan.

Table 8.10. Estimate of Long Term Development Costs Water Development & Soil Conservation (In 1990 dollars)

COMPONENT	PHASE 1 1990-1995	PHASE 2 1995-2000	PHASE 3 2000-2005	PHASE 4 2005-2010	TOTAL
I. GROUND WATER					
Drilling Program	1,367,000	525,000	525,000	0	2,417,000
Well Renovation	53,000	12,500	6,000	0	71,500
Storage Facilities	150,000	225,000	110,000	0	485,000
Distribution Facilities	89,000	249,000	249,000	0	587,000
Misc. Pumps & Controls	150,000	70,200	110,000	0	330,200
Water Quality Treatment	45,000	45,000	12,000	12,000	114,000
Operation/Maintenance	50,000	50,000	50,000	50,000	200,000
SUBTOTAL	1,904,000	1,176,700	1,062,000	62,000	4,204,700
II. RAINFALL HARVESTING					
Storage Capacity	210,000	110,000	105,000	10,000	435,000
Catchment Construction	265,000	160,000	210,000	20,000	655,000
Distribution	80,000	55,000	55,000	10,000	200,000
Operation/Maintenance	25,000	25,000	25,000	25,000	100,000
SUBTOTAL	580,000	350,000	395,000	65,000	1,390,000
III. DESALINIZATION					
Equipment	43,500	43,500	43,500	14,500	145,000
Storage Facilities	27,000	27,000	27,000	9,000	90,000
Distribution Systems	3,000	3,000	3,000	1,000	10,000
Operation & Maintenance	55,000	75,000	100,000	110,000	340,000
SUBTOTAL	128,500	148,500	173,000	134,500	585,000
IV. SOIL-WATER CONSERVATION					
Soil Erosion Control	450,000	450,000	450,000	145,000	1,800,000
Sediment Detention	27,000	13,500	13,500	13,500	67,500
Runoff Harvesting	55,000	55,000	110,000	10,000	230,000
Revegetation	450,000	450,000	450,000	450,000	1,800,000
Operation/Maintenance	25,000	25,000	25,000	25,000	100,000
SUBTOTAL	1,007,000	993,500	1,048,500	948,500	3,997,500
TOTALS	3,619,500	2,668,700	2,678,500	1,210,000	10,176,700
Construction Allowance	1,701,165	1,254,289	1,258,895	568,700	4,783,049
GRAND TOTAL	**5,320,665**	**3,922,989**	**3,937,395**	**1,778,700**	**14,959,749**

Notes to Chapter 8

[1] The differing objectives for land use control and management between the community and the U.S. Navy suggests a need for dialog and education so the differences do not become barriers to effective resource management.

[2] State of Hawaii, State Water Code, Hawaii Revised Statutes, Chapter 174C. The Consent Decree also provides standing to the Protect Kaho'olawe 'Ohana in matters regarding the resources of Kaho'olawe. Finally, the history of land use and the cultural concerns with Kaho'olawe on the part of the local community would mandate community participation in decisions regarding ground water use.

[3] The present negotiation arena offers a potential avenue to direct and control resource management strategies.

Chapter 9

Conclusions and Recommendation

Conclusions and Recommendations

The completion of the Kaho'olawe Water Study marks a new era in the rehabilitation of the island's soil, water and vegetative environment. First, the examination and management of the water resource has served to provide a framework through which all natural and cultural resource management activities can be combined to proceed successfully. Second, the efforts of a private community agency, the Protect Kaho'olawe 'Ohana/Fund, proved the existence of a successful and viable mechanism for the implementation of soil and water conservation goals and activities on Kaho'olawe. Finally, the demonstration of the island's water resource potential through both runoff and rainfall harvesting, the demonstration of effective means of erosion control through soil and water conservation techniques, and the development of a medium for vegetation growth on Kaho'olawe provide evidence that coordinated and comprehensive approaches to Kaho'olawe's resource environment can succeed.

Accordingly, the following recommendations are intended to provide a framework for the continuation of immediate resource conservation activities as well a direction for the development of a long-term strategy for the rehabilitation of Kaho'olawe's natural resource environment.

Recommendation One. A minimum of $2.5 million over the next two years should be committed immediately to support the critical revegetation and soil conservation work needed for Kaho'olawe. Specifically, an active water development program for the island should begin as soon as possible and should consist of: (a) the renovation of existing and development of new runoff catchment systems, (b) rainfall harvesting programs and (c) ground water development.

Recommendation Two. Resource management activities on Kaho'olawe should continue with a program focused on the construction of effective check dams and headcut control structures in the tamarisk tree area, the development of water supplies, revegetation of selected areas and the development of specific erosion control projects for critically eroding regions of the hardpan area.

Recommendation Three. A Kaho'olawe Watershed Restoration Task Force should be established to coordinate, oversee and implement the stabilization of approximately 15,000 acres of severely eroded land on Kaho'olawe over a 5-10 year period. The Task Force should be composed of all organizations and agencies actively pursuing resource management activities on the island including the Protect Kaho'olawe Fund, high-level staff and the director from the State Department of Land and Natural Resources, and the U.S. Navy as well as members of the State Legislature, appropriate technical personnel from the University of Hawai'i, the East-West Center, the Maui County government, the U.S. Soil Conservation Service and the U.S. Geological Survey. The Task Force should seek ways to coordinate the development and use of funds and government resources for Kaho'olawe watershed activities.

Recommendation Four A comprehensive examination and evaluation of the U.S. Navy's program for resource management and soil conservation and the Navy's land use activities on Kaho'olawe must be undertaken, as specified in the Consent Decree. As specified in the same Decree, appropriate modifications must be made if found to be in conflict with overall land stabilization goals.

Recommendation Five. A comprehensive examination and evaluation should be undertaken of the State Forestry program, particularly in regards to the planting of tamarisk trees parallel to the direction of water flow in critical watersheds and planned in coordination with other conservation measures.

Recommendation Six. In keeping with mandated historic preservation directives, the pace of archaeological site stabilization through the control of water-induced soil erosion, must increase dramatically over the next few years if existing sites are to remain in tact. Cultural resource management must be a priority for all resource agencies on Kaho'olawe and site stabilization activities integrated with overall resource use management on Kaho'olawe. The State Historic Preservation Division and the U.S. Navy, working with the Protect Kaho'olawe 'Ohana, must immediately resume management activities including: (a) the completion of a new survey of sites to establish baseline conditions that have changed since 1980 and to serve as a guideline for site stabilization and (b) the immediate stabilization of some 8,000 acres of threatened archaeologically-rich land and individual sites on Kaho'olawe's eroding hardpan.

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